COMBUSTION TESTING OF A PILOT SCALE EXPERIMENTAL FURNACE

BY

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COMBUSTION TESTING OF A PILOT SCALE EXPERIMENTAL FURNACE

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PREFACE

The primary purpose of this study was to test a pilot scale experimental furnace using natural gas or coal. The furnace was found to be operative for long periods of time using natural gas or coal.

I wish to express my sincere gratitude to all the people who assisted me in my work. I am especially grateful to my major advisor, Dr. Arland H. Johannes, for his expertise and valuable assistance. I am also thankful to my other committee members, Dr. M. Seapan and Dr. R. C. Erbar for their cooperation in the course of this study.

I am also thankful to Mr. Sheng Wang and Mr. Nadir Kamal for their valuable assistance during this study. Special thanks to the School of Chemical Engineering for their financial support.

Finally, I wish to appreciate my family for their moral and financial support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The abundance and the low cost of recovery of U.S. low rank coals has made them an appropriate candidate for fuels for combustion boilers of power generating utilities. In addition, regulations passed in 1979 require plants to burn coal instead of natural gas and oil. These regulations were passed to increase energy and natural resource conservation. However, the combustion behavior of low rank coal presents many serious problems such as slagging, fouling and corrosion which may eventually lead to the shutdown of a power plant.

In order to meet the federal and the state SO_2 emissions limits, many coal fired power plants have started to blend high sulfur coal (>3% sulfur) and low sulfur coal (<1% sulfur). The Environmental Protection Agency (EPA) limit for sulfur dioxide emissions for new facilities is 1.2 lbs SO_2 per million BTU fired. Most of the existing facilities do not meet these limits. Other reasons for blending coals include reduction in operating capital costs, increase in average BTU content and balancing the heating values of the coals to balance the fluctuation during operation. Blending will also increase due to spot

market purchases by power plants. The state of Oklahoma requires that the power plants operating in Oklahoma use at least 10 percent Oklahoma coal.

There are also many problems associated with using pure and blended coals. From past experience, it has been established that slagging and fouling are more serious when two or more coals are blended and used for combustion purposes. At present, nobody is able to predict combustion problems during operation with high percent accuracy. Presently, there is a substantial amount of research into the effects of blending coals. Many different models have been presented to predict slagging and fouling in boilers but these models only apply to specific cases and they can not be generalized over the wider range.

All coals contain some mineral matter and when coal is burned this mineral matter is converted into ash. Ash is formed as a result of reactions occurring when mineral matter is heated above some critical temperature so that a liquid phase is produced in a portion of the material. This forms deposits in boilers. The ultimate result is slagging in the radiation zone and fouling in the convection zone. These deposits reduce the heat transfer rate hence reducing boiler efficiency and may even result in plant shutdown. The major coal quality impact areas in a boiler are shown in Figure 1.

This unexpected problem also occurred at the Public

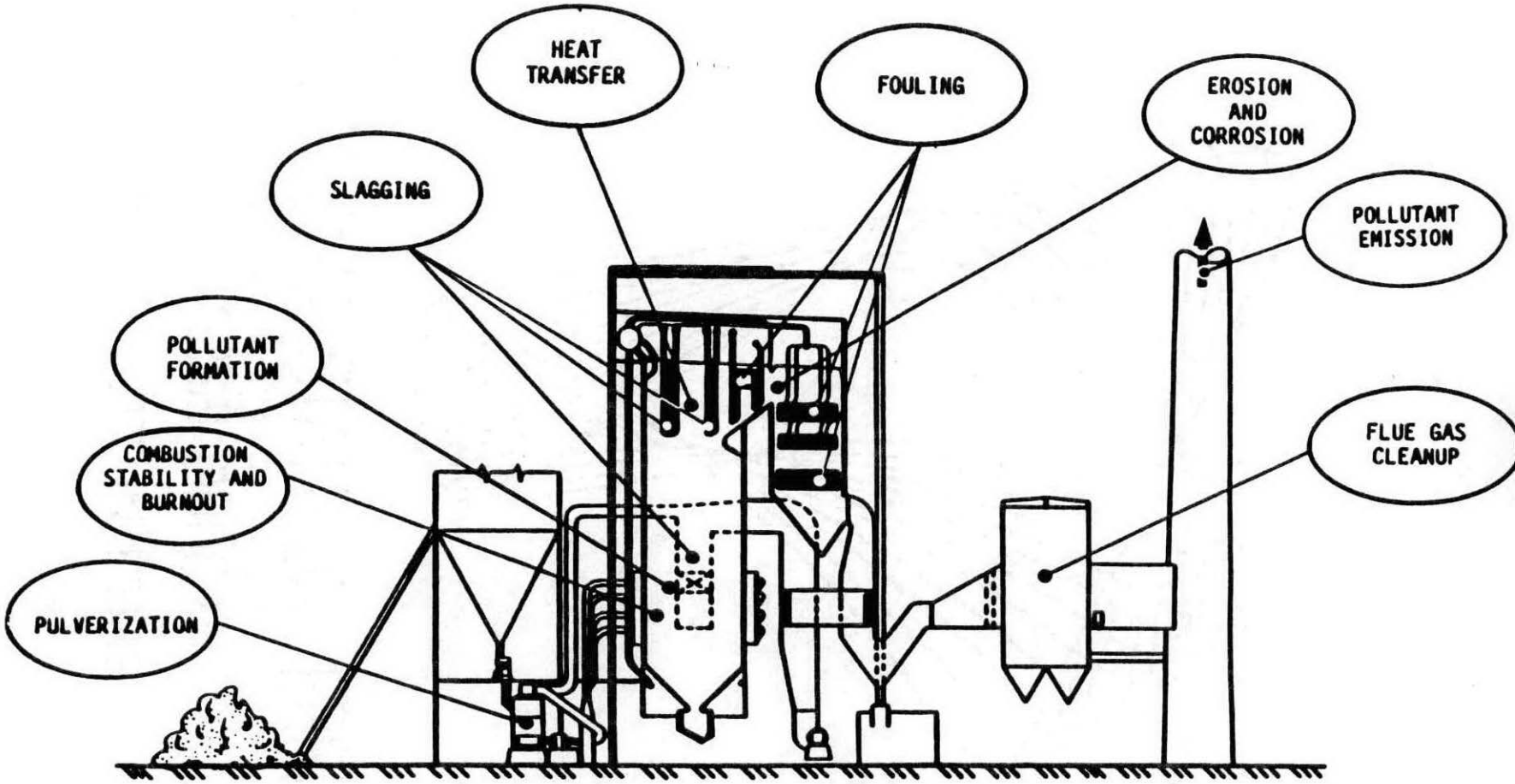

FIGURE 1. SCHEMATIC DIAGRAM OF UTILITY BOILER SHOWING AREAS WHERE COAL IMPACTS ON BOILER OPERATION (12)

Service Company (PSO) of Oklahoma's Northeast Power Generation Station in Ooologa, Oklahoma, during 1981 and 1982. At that time, they were using blends of Jacobs Ranch and Clovis Point, Wyoming coals. Severe slagging and fouling problems were correlated to a combustion of blends of 75% Jacobs and 25% Clovis coals. This problem finally caused the boiler shutdown. Presently, there is no specific method to predict slagging and fouling caused by blending of these coals. PSO contacted Dr. Johannes, Dr. Seapan and Dr. Foutch at Oklahoma State University to investigate their problem. At this time, research is being conducted at Oklahoma State University under Dr. Johannes and Dr. Seapan's supervision to investigate the relationship between coal blending and slagging and fouling.

For this research, a laboratory scale furnace was built by Shen Wang for his masters thesis (Shen Wang, 1987). The furnace is designed to have the following characteristics.

1. A combustion situation in the boiler similar to that used by power plant in terms of operational temperature and residence time.
2. Any desired proportions of blended coal can be used in the furnace.
3. The slagging and the fouling samples can be collected easily.

The objectives of this research were to test the furnace to see if it could be operated using natural gas and coal and then study the characteristics associated with combustion in this furnace.

The first step in this research is to add new facilities in the laboratory to make it more compatible with the real combustion situation. These new additions will also help in providing useful data. The second step in this research is to calibrate and test the major equipment to see if they are working properly.

After accomplishing the first two objectives, the third step is to operate the furnace using natural gas. If satisfactory results are achieved then material balance and energy balance will be performed on these runs to find the amount of leakage in gases and energy loss from this furnace.

The last and the most important step in this research will be to operate this furnace using coal. Clovis Point coal will be used in these runs. If the furnace proves to be operative with Clovis Point then it will be checked to see if any slagging and fouling samples can be obtained from the furnace.

In brief, this furnace has never been tested before for long runs using natural gas or coal. The existing laboratory lacks a few facilities before it can be operated for useful purposes. The objective of this study is to add

new equipment. Then test the furnace for natural gas and coal.

CHAPTER II

LITERATURE REVIEW

The Electric Power Research Institute (EPRI), the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA) and other organizations are conducting different programs to develop efficient and reliable advanced technologies to generate electricity from coal in an environmentally acceptable manner. These advanced technologies include fluidized bed combustion, coal gasification and combined cycle, and coal liquefications. Most of these technologies will not be available for commercial applications until the early 1990's.

In the mean time, coal fired generating capacity is provided by conventional pulverized coal fired units. The U.S. coal production was projected to increase from 670 millions tons per year in 1977 to about 1100 million tons per year in 1985 and in this period the utility industry would install about 110,000 MW of new coal fired generating capacity (McGowin, 1977).

This chapter is divided into four parts. The first part discuses mineral matter in coal. The second part discuses slagging in boiler furnaces. The third part

discuses application of pilot scale testing and the fourth part discuses additives to prevent slagging and fouling.

Mineral Matter in Coal

In the U.S., in 1981, almost 500 million tons of coal were burned annually in boilers to produce steam for electricity generation. Coal contains some kind of mineral matter and when coal is burned this mineral matter is converted to ash. Coal ash has very adverse effects on boiler performance. Coal consists of two parts, combustible and non-combustible. The non-combustible part typically makes up 5 to 30 percent of the total coal. This non-combustible portion is commonly called coal ash. This portion contains all the inorganic material found in coal. The most abundant non-combustible species in coal are alumino-silicate clays. Along with quartz they make up to 60 to 90 percent of the non-combustible part in the coal (Zecchini, 1986). All elements in coal except organically combined C, H, O, N and S are classified as mineral matter. Slagging is the accumulation of mineral matter in a fused and hardened form on the walls in the radiation zone and fouling is the accumulation of mineral derived ash on the superheater in the convective zone of the furnace (Harvey and Ruch, 1986). Mineral matter can also affect other furnace parameters such as deposit's thermal conductivity and deposit's particle size. Thermal conductivity of the

deposit influences the thermal efficiency of the furnace. Thermal conductivity is also dependent on composition, porosity, density and structure of the ash deposit. Minerals like calcium, iron, magnessium and sodium affect the thickness of deposit layer (Smith et al., 1988).

Smith et al.(1988) also conducted a study to analyze the effects of coal quality on furnace performance. The properties measured during the experiment were ash emittance, thermal conductivity and deposit thickness. The data were collected using two Utah coals. It was found that lower than designed grade coals caused severe problems in furnaces. Thermal conductivity, emittance and thickness of wall ash deposit were found to be critical to the furnace performance.

Slagging in Boiler Furnaces

Slagging takes place in the radiation zone when coal is burned and inorganic matter in coal is converted to an incombustible ash residue. D.O.E. has conducted research on the sticking temperature of a molten slag (Barnes, 1979). A test was performed in which a small pellet of coal ash was sintered around the platinum loop. This platinum loop was then lowered into a vertical refractory tube. A flame was directed at the pellet. This caused the molten slag droplet to fall off the wire on to the metal substrate. The substrate temperature was varied using

heating coils. The droplet solidified on touching the substrate when the temperature of the substrate was above the sticking temperature. When the metal surface temperature was below the sticking temperature, the droplet did not adhere to the surface. It was also found that adding FeO to coal ash decreased the sticking temperature.

Abbot and Austin (1985) conducted a study on the sticking behavior of slag drops. Three sample coals were used. A partial separation of sample coals into specific gravity fractions was used to prepare ashes enriched in certain inorganic matter. The Moza-Austin sticking test was used to investigate the sticking behavior of slag drops formed from low temperature ash. The heavy gravity fraction of low temperature ash showed more enhanced adhesion properties compared to the whole coal low temperature ash. This suggested that pyrite was a major cause of the initiation of slag deposits. From this study it was concluded that coals which contain pyrite and glass forming minerals in a 3:1 ratio will show greater slag deposit tendencies. Abbot and Austin (1985) also studied the effect of flame temperature on the adhesion of slag drops to oxidized boiler steels. Increase in adiabatic flame temperature also increased the strength of adhesion to the substrate.

Shell Research Ltd of the UK conducted a study of aerodynamic influences on ash formation during pulverized

coal combustion (Unsworth et al., 1987). This study was prompted by unexpected results obtained using Austrailian coals. Initially slagging problems were experienced using Austrailian coal which contained high concentrations of iron and calcium. When this coal was blended with another coal having an even higher iron content, slagging was unexpectedly reduced. The tendency of particle size to follow in a curved stream line is controlled by inertial forces and aerodynamic drag. The higher the particle density, the greater are the chances of the particle hitting the boiler walls and being retained within the deposit. Particles with low density flow out as fly ash. Char samples were prepared and were tested with coal samples. Air classification was used to separate coal and char particles according to their bulk density differences. The ash properties of the resultant fractions were then compared. The ash was found to be more fusible for coals and chars of high and low bulk density whereas ash from intermediate fraction was found to be more refractory. The following trends were found for highest density bulk:

1. Fe_2O_3 was very concentrated in all samples.
2. CaO was more concentrated in coals but is distributed all over in char.

Sanyal and Williamson (1981) developed an assessment technique based on thermal behavior of coal mineral to predict the slagging properties. Ashes from two different

South African coals with different mineralogical constituency were prepared under low temperature ash environment. These ashes were then analyzed by X-ray powder diffraction. Slag samples were prepared by heating ash samples up to 1550°C and then slowly cooling it down to 900°C. Glasses and crystalline products produced by this technique were examined by optical micro-analysis. In one of the samples, the glass product had a higher CaO content. These two ashes had similar fusion characteristics but different melting and crystallization behavior. An ash sample with high CaO produced a fluid slag which crystallized to form a crystalline mass while the other ash sample with low CaO produced a viscous melt which eventually formed a higher residual glass content. It was found out that this hot stage microscopy technique can be very useful in predicting the slagging behavior.

Austin et al. (1987) conducted a research at Pennsylvania State University to study the mechanisms of slag deposit formation. A laboratory scale vertical combustion tube was used. Pulverized coal was combusted under conditions similar to a full scale boiler. Coal particles were injected into the hot zone (1500°C) of the vertical tube furnace. The types of fly ash formed in the vertical tube varied in the same way as the distribution of the inorganic constituents in the coal. The factor that influenced the formation of fly ash was found to be the

gaseous environment at the surface. The environment could be either very reducing or highly oxidizing. Under reducing conditions, volatilization of inorganic material occurred easily. Studies of ash formation in this tube showed that stronger ash deposits contained abundant crystalline material but the weak deposits did not contain crystalline material.

The deposit strength was affected by a sodium containing melt phase. This melt phase dissolves other ash components and results in major sintering in the deposit. The fly ash and products of combustion were then impinged on a water cooled oxidized boiler steel substrate. Very soon a deposit formed over the entire surface. As the deposits grew and were exposed to higher temperature (>1000°C), low viscosity liquid materials were produced in the deposit. This liquid is responsible for strength due to sintering. Hence it was concluded that quality and composition of the liquid phase present in the deposit influenced the deposit strength.

Application of Pilot Scale Coal Testing

Coal combustion testing at the pilot scale has been conducted for several years by boiler utilities in order to have a better understanding of the impact of coal characteristics on boiler operation.

One of the pioneers in this field is the U.S. Bureau

of Mines (Kurtzrock et al., 1963). A laboratory scale furnace was built by them to handle 1 to 4 lb. of coal per hour. The complete unit consisted of coal preparation and feeding system, furnace, instrument panel and analytical system. The furnace was fired vertically downward into the primary combustion chamber which was 1.5 cubic ft. in volume. The secondary chamber was 1.8 cubic ft. in volume. Two natural gas burners were provided for preheating the furnace to operating temperature of 1800°F to 2000°F before admitting coal. The performance of the furnace was determined at coal feed rates of 1, 2 and 4 lb per hour with combustion air at 125 percent of the stoichiometric requirements. The ratio of tertiary air over secondary and primary air was 2:1. It was found that erratic flames are produced when the coal feed rate was less than 2 lbs. per hour or when the temperature was less than 1750°F. In all three cases combustion air was preheated to 500°F. The best operating conditions were attained with using 2 lb of coal per hour. Table I shows the effects of excess air on combustion efficiency when burning 2 lb of coal an hour.

Another furnace was built by M.E.How (1954). This furnace was designed to burn pulverized coal at 2.5 to 4.0 lb per hour without the need for external heat for maintaining a stable flame. The furnace was made of sillimanite brick. About 20 percent of the total combustion air used was from the primary air and the

secondary air supplied 50 percent of the combustion air. The rest was supplied by the tertiary air. The secondary and the tertiary air supplies were preheated to 400°F. Flue gas analysis was done using an Orsat analyzer. The combustion chamber was fired vertically from the top by a small burner consisting of three concentric tubes. The rate of heat release, gas temperature, metal temperatures and residence time of the coal particles were similar to those obtained in a large pulverized coal boiler. Effect of excess air on gas temperatures and percentage of carbon in fly ash can be found in Table II.

These two experiments were carried out a long time ago. The first furnace is still being used to investigate slagging problems. EPRI was contacted to provide information about new pilot scale testing facilities from all over the world (Johnson et al., 1988).

Rheinisches Westfaelisches Elektrizitatswerk (RWE) of West Germany constructed a pilot scale facility to investigate the related processes of ignition, combustion and subsequent ash fouling in brown coal flames. The research facility consists of a roof fired, refractory-lined and steam cooled chamber 4 feet in diameter and 20 feet long. The furnace was designed to handle a maximum of 1100 lb per hour of raw brown coal. Steam-cooled slag panels were inserted in the wall of the combustion chamber

TABLE I

EFFECT OF EXCESS AIR ON COMBUSTION EFFICIENCY
IN BURNING 2 LB OF COAL AN HOUR (13)

EXCESS AIR PERCENT	GAS ANALYSIS VOLUME PERCENT WATER FREE			CARBON IN FLY ASH WEIGHT PERCENT
	CO_2	CO	O_2	
5	17.9	0.0	1.1	6.6
15	16.5	0.0	2.7	3.0
25	15.1	0.0	4.2	2.0

TABLE II

EFFECT OF EXCESS AIR ON GAS TEMPERATURES
AND PERCENT OF CARBON IN FLY ASH (11)

		TEMPERATURES F			
CO_2%	EXCESS AIR%	THERMO COUPLE 1	THERMO COUPLE 2	THERMO COUPLE 3	CARBON IN FLY ASH %
8.0	130	1595	-	870	22.0
10.1	80	1790	1600	820	-
12.5	46	1900	1750	795	8.5
14.2	28	1930	1800	775	-
17.5	5	2000	1880	745	25.9

Thermocouple 1: Primary Chamber
Thermocouple 2: Exit of Combustion Chamber
Thermocouple 3: Secondary Chamber

at various distances from the burner. Fouling test banks were also inserted into the flue gas in the horizontal and vertical sections of the convection duct. Investigations showed sulfur and alkali contents affected the nature of the deposits. Increasing the sulfur and alkali content and decreasing the calcium concentration causes more severe fouling. This effect is shown in Figure 2. It was also found out that the maximum deposition rate occurred at locations near the peak flame temperature. Another very important finding was that combustion parameters played an important role in deposit formation, especially excess air rate and the rate of mixing between fuel and air in the burner region. The reason being that with low excess air or poor mixing between air and fuel, a high percent of sulfur forms sulfides as found in the fly ash taken in the flame. The sulfides have lower melting points than the comparable sulfates and the presence of sulfides in the fly ash means a greater portion of molten ash material thus leading to lower gas temperature. This increases the deposits growth and makes the bonds stronger. Recent conversation with Dave Lehman of PSO also confirmed that they have minimized their slagging problems by increasing the excess air. Ontario Hydro (OH) of Canada have recently constructed a pilot scale combustion facility. The furnace is approximately 2.75 by 1.75 foot cross section by 9.75 feet high from bottom hopper to steam drum. The furnace

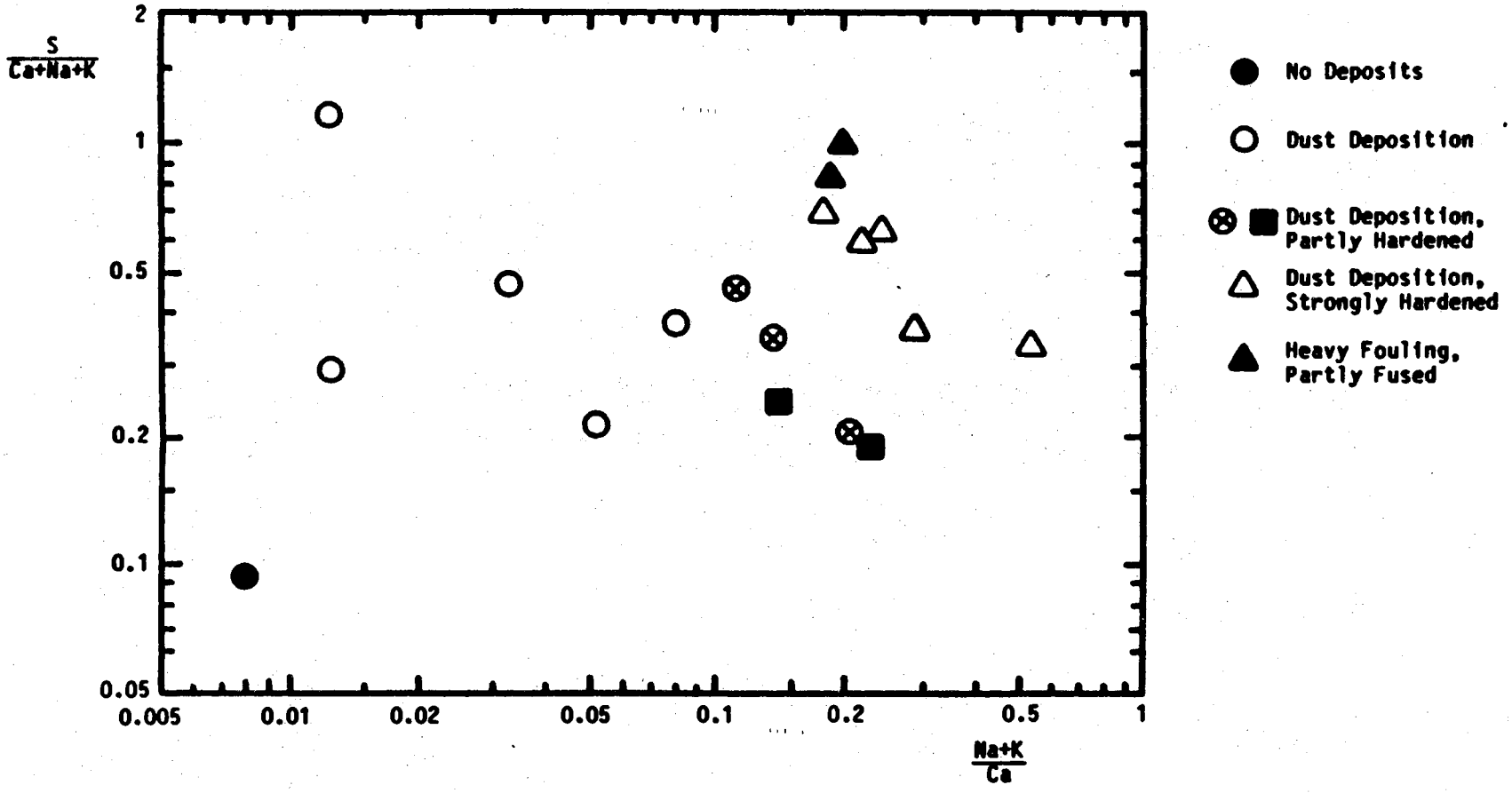

FIGURE 2. OBSERVED FOULING TENDENCIES, MOLAR RATIOS IN RAW COAL (RWE) (12)

can handle 200 lb per hour of coal. The furnace outlet temperature was 1870°F. Five different combinations of coals were tested. The combinations included 100% U.S. coal, 50/50 blends with U.S. coal and three component blends. Ash deposition was monitored by an air cooled probe. It was concluded that the rate of deposition with coal blends was lower than that when using the regular U.S. coal alone. This difference was attributed to the higher iron content in the U.S. coal.

In the U.S., utilities have been using substantially large amounts of low rank coal. Some of these coals have caused severe slagging and fouling. Earlier studies showed that these problems were associated with high levels of sodium in the inorganic part of coal. The effect of this kind of coal was tested at the Hoot Lake No.2 unit of Otter Tail Power Co. This unit is a pulverized coal, tangential fired unit. High sodium lignite was used for the first test. Within three days, the boiler accumulated so much material due to slagging and fouling that it had to be shutdown. Another test was done using a lower loading of the same coal and it was found that the unit had to be shutdown after nine days. After running several runs with coals of different strength of sodium lignite, it was found out that coal with lower Na_2O improved the boiler performance.

Additives to Prevent the Boiler Slagging

In the early 1960's, magnessium oxide was successfully injected to minimize the fouling of heat absorbing surfaces on coal fired boilers but the amount required, 0.4% to 3% of the fuel, was very uneconomical. In the late 1970's it was found that MgO dispersions of finer particle size of produced better results with low treatment rates of 0.015% of the fuel. Radway and Boyce (1978) investigated this case. They ran a series of tests on a pulverized coal fired industrial boiler. The unit used 3.5% sulfur coal from Ohio with a moderate fouling index. They used a temperature controlled deposition probe to investigate the effectiveness of magnessium oxide. Treatment rates varied from 150 to 1250 ppm MgO and probe temperatures were held at 500°C to 610°C. Screen tubes and wall tubes exposed to the additive showed 85% to 90% less deposit accumulation than on the tubes not exposed to the additive. Sodium and potassium are volatilized from the mineral matter in coal at high temperature to form Na_2O and K_2O. During combustion, pyrites are dissociated thermally and form SO_2 and SO_3 after reacting with organic sulfur in the coal. Na_2O and K_2O react with SO_3 to form sulfate deposits on the tube. Rodway and Boyce concluded that addition of magnesia reduced the formation of SO_3 from SO_2 by covering the catalytic iron oxide surfaces in the boiler.

Additives containing magnessium oxide and aluminum oxide ($MgAl_2O_4$) are also used to decrease slagging and fouling problems. This additive raises the melting point of the fly ash deposits and if the contacting surface temperature is much less than the melting point of fused ash compounds, these residuals are carried out through the stack by particulate emission (Dixit and Cuissa, 1977).

Another effective product has been formulated to improve combustion and to control deposits and corrosion in coal fired units (Oschell and Boccuzi, 1980). This product is called FST-6000. It is a unique mixture of several metallic compounds. FST-6000 was evaluated in a Babcock and Wilcox spreader stoker. The percent of carbon dioxide in flue gas was monitored before and during treatment with FST-6000. The results are shown in Table III.

Fly ash and bottom ash samples were taken before and after treatment. The results are shown in Table IV. The overall results achieved were:

1. An increase in the CO_2 concentration and reduction in the O_2 concentration in the flue gas.
2. A reduction in the stack temperature.
3. A reduction in the deposits on the surface of the boiler.

From the above literature survey one concludes, there is no single model at this time that can predict slagging and fouling in boilers. Another case of this lack of

TABLE III

CARBON DIOXIDE CONCENTRATIONS IN FLUE GAS (7)

CO_2%	
WITHOUT TREATMENT	WITH TREATMENT
12.5	13.0
12.9	13.4
12.5	12.9
12.4	12.9
12.5	13.0

TABLE IV

COAL ASH ANALYSIS (7)

	TOTAL CARBON PERCENT	
	WITHOUT TREATMENT	WITH TREATMENT
BOTTOM ASH	8.4	5.2
FLY ASH	55.8	49.4

predictivity was seen in the two instances when a reduction in slagging was observed on blending two or more coals. A general impression that blending increases slagging has previously been held by workers in this field.

CHAPTER III

EQUIPMENT LAYOUT

This chapter discuses the experimental equipment. A flow chart of the whole unit is shown in Figure 3. This chapter is divided into four parts. The first part discuses the furnace and the stack. The second part discuses the coal feeding system. The third part discuses the supply and the control system. The fourth part discuses the measurement system.

The Furnace and the Stack

The furnace includes one coal burner, two natural gas burners, one tertiary air burner, three sight holes, two sampling ports, two cleanout ports, two heat exchanger banks and one pressure relief valve (Shen Wang, 1987). The furnace is enclosed in a steel shell. The furnace wall is composed of three layers of bricks. Each layer is 4.5 inches thick providing a total thickness of 13.5 inches. This provides good insulation and prevents heat loss. The inner layer is made of alumina refractory brick which can withstand a temperature of 3300°F. The middle and the outer layers are composed of insulation brick with an upper operating temperature of 2000°F. The total weight of the

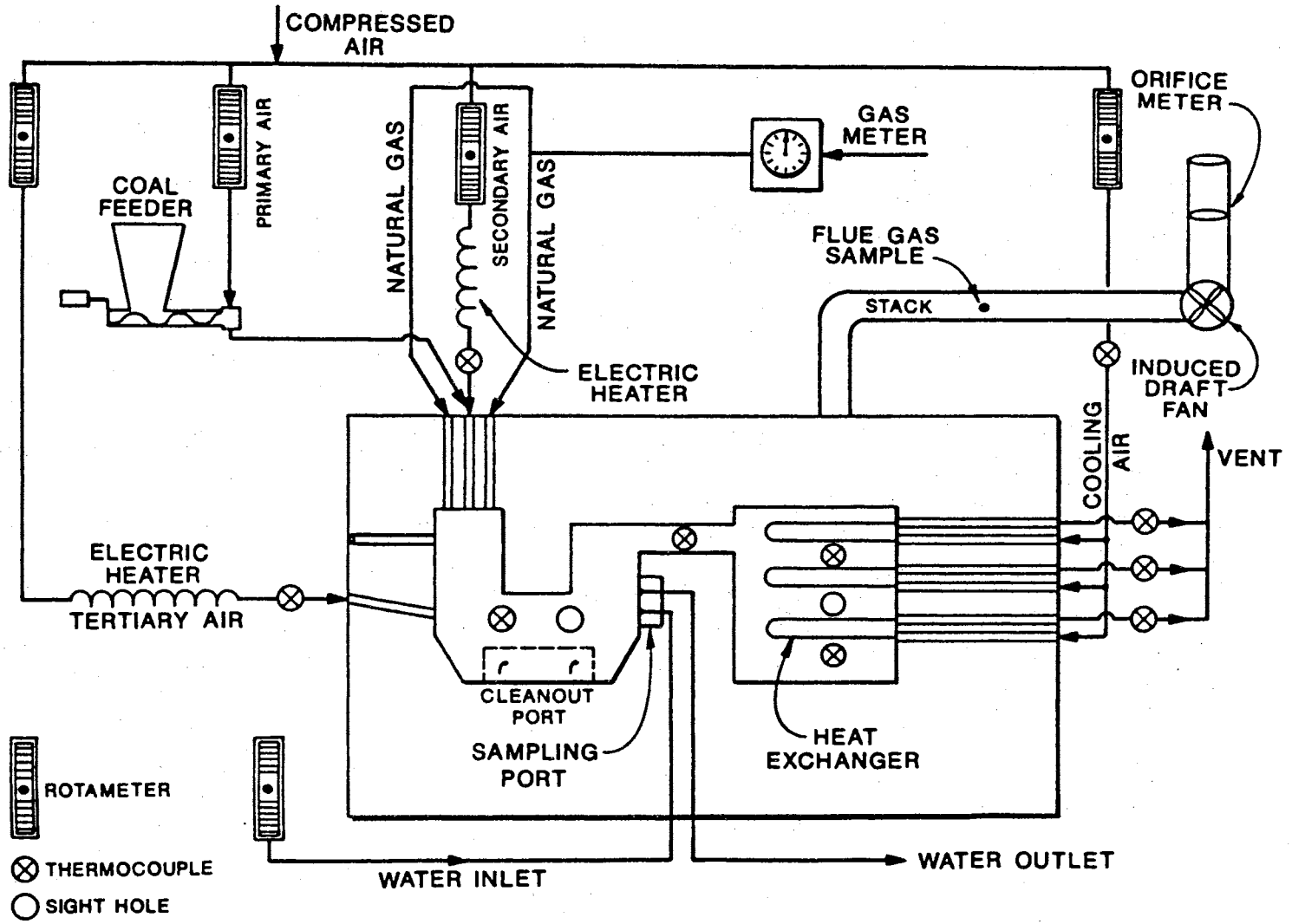

FIGURE 3. SCHEMATIC FLOW CHART OF EXPERIMENTAL SET UP

furnace is over 3 tons.

The furnace is divided into two chambers; the primary chamber and the secondary chamber. The first chamber has a volume of 1.8 cubic ft and the second chamber has a volume of 2.2 cubic ft. All the combustion air inlets go into the primary chamber. There are two natural gas burners located at the top of the primary chamber. The pulverized coal burner is located in the center of the burner block between the two natural gas burners. The primary chamber serves as the radiant zone, slagging samples are expected to be obtained from the sides of this chamber. There is one cleaning port and one sampling port in the primary chamber. The sampling port consists of two parallel stainless tubes embedded in a refractory brick. This sampling port is a water cooled heat exchanger surface. Cold water enters in these tubes through a 1/2 inch pipe and leaves as hot water through a 1/2 inch pipe. Slagging samples can be collected on this sampling surface.

The secondary chamber is connected to the primary chamber by the throat which has a cross sectional area of 22 square inches. This small area causes the velocity of the combustion gas to increase and it also prevents the flame in the primary chamber from passing into the secondary chamber. The secondary chamber has one cleaning port, one sampling port and two heat exchangers. The sampling port is for collecting fouling samples. It also

acts as a heat exchanger. These heat exchangers use air as the cooling fluid. The main purpose of these heat exchangers is to cool down the combustion gases to a suitable temperature for stack gas analysis.

A stack gas pipe is located at the top of the furnace at the back of the secondary chamber and is used for carrying the combustion gases. The stack is 4 inches in diameter. The stack is double walled for good insulation. There are two small openings in the stack for collecting flue gas samples. The induced draft fan is located between the stack hence dividing the stack into two parts. The purpose of the induced draft fan is to control the pressure in the furnace which prevents the flame and the combustion gases from coming out, by creating a negative pressure in the furnace. An orifice meter has been installed in the second part of the stack. The pressure drop across the orifice meter will allow calculations of the flow rate of the flue gas.

To make sure there is minimal leakage of air, Sairset mortar was used to seal the small openings around the joints in the furnace. The front door of the furnace can be removed by the removal of the 14 bolts. The detailed procedure is given later on in chapter IV.

Coal Feeding System

Coal is fed by a commercial unit made by the Vibra-Screw Company of New Jersey. The coal feed rate can be varied by a variable speed drive. The feeder assembly is continuously vibrated to ensure complete filling of the screw and provides uniform feeding of pulverized blended coal. The coal is sent to the edge of a T pipe by vibrations caused by the feeder. From there on the coal is carried by the primary air to the coal burner. A photograph of this assembly is shown in Figure 4.

Supply and Control System

There are four air supply lines, one natural gas line and one water supply line. Four air supply lines are for the primary air, the secondary air, the tertiary air and the cooling air for the heat exchangers. These air supplies are monitored using rotameters. Attached to these rotameters are pressure regulators to control the pressure of air coming out of these lines. As mentioned before, the primary air carries the coal to the burner.

The secondary and the tertiary air are preheated, using heating coils with the help of powerstats, before entering the furnace. Preheating is required to maximize the temperature conditions in the furnace. An advantage of powerstats is that the inlet temperature of the secondary

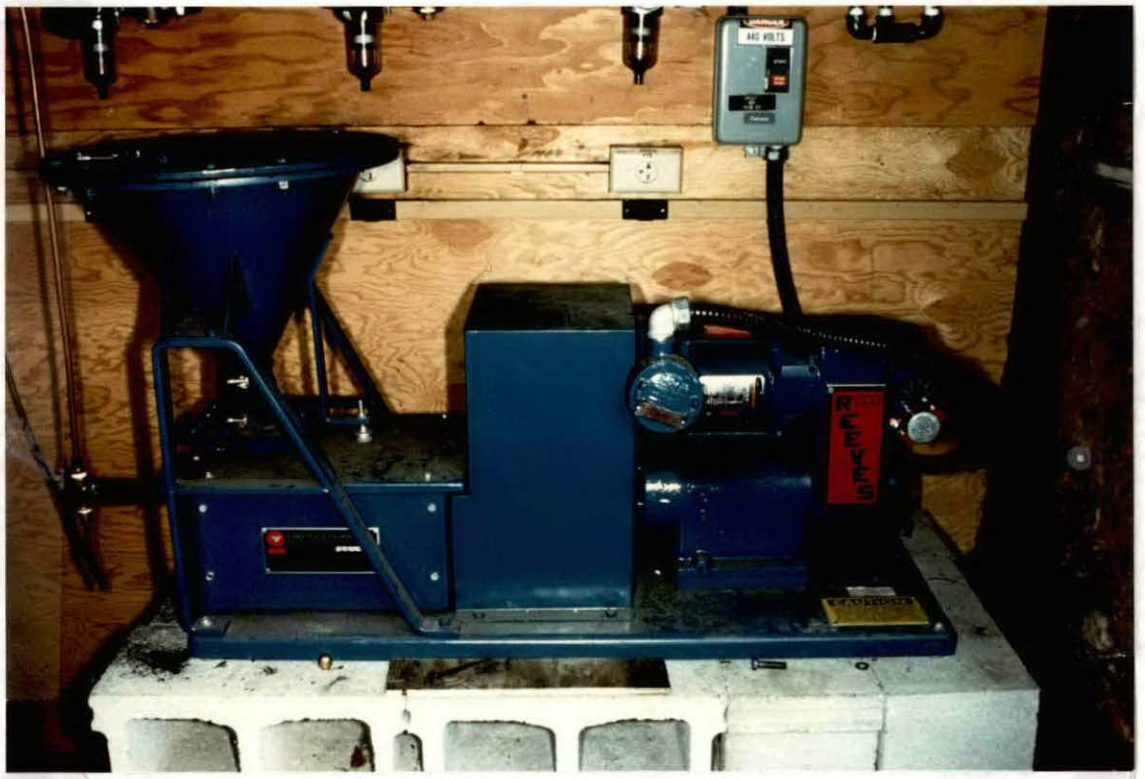

FIGURE 4. COAL FEEDER

and the tertiary air can be controlled. The pipes carrying the secondary and the tertiary air are insulated by using glass wool. This is done for two reasons. The first is the safety. These pipes are at very high temperature and any physical contact with them can be dangerous. The second to prevent heat loss. The natural gas supply is controlled by two valves. The flow rate of the natural gas is monitored by a dry gas meter. The natural gas is used for the initial ignition and the furnace preheating. Water for the sampling port is also controlled by a rotameter. The controlling equipment mentioned above serve two purposes. The first is to control the supply of fluid and the second is to provide information on the amount of fluid used.

Measuring System

The temperature in the furnace is measured by high temperature type R, Pt-Pt 13% Rh platinum thermocouples. The thermocouples are covered in ceramic protected tubes. Initially there were seven thermocouple locations but later on five additional thermocouples were added. All thermocouples are connected to a digital monitor. The thermocouples locations are given below:

1. Thermocouple #1 and thermocouple #3 measure the temperatures in the primary and the secondary chambers, respectively.

2. Thermocouple #2 measures the temperature in the throat connecting the primary and the secondary chamber.
3. Thermocouple #4 measures the temperature of lower wall of the secondary chamber.
4. Thermocouple #5 measures the flue gas temperature as it leaves the furnace and enters the stack.
5. Thermocouple #6 and thermocouple #7 measure the temperatures of the tertiary and the secondary preheated air.
6. Thermocouple #8 measures the temperature of the water outlet from the primary chamber's sampling port.
7. Thermocouple #9, thermocouple #10 and thermocouple #11 measure the temperatures of the air coming out of the heat exchangers of the secondary chamber.
6. Thermocouple #12 measures the temperature of the cooling air for the secondary chamber's heat exchanger.

Flue gas samples are collected using a suction pipe. These gas samples are then sent to the Orsat meter. There are two Orsat meters. The first one contains potassium hydroxide solution and it measures CO_2 content of the flue gas. The second one contains chromous chloride solution and it measures O_2 content of the flue gas.

The first step in this research was to add more facilities to the already existing facility (Shen Wang, 1987). This was done in order to increase the efficiency of the system and also to obtain useful data. The main

objective of Shang Wang's thesis (1987) was to built the furnace. His work did not establish, if the furnace would work using natural gas and coal. The main objective of this research is to determine if the furnace could be operated using natural gas and coal.

Five more thermocouples #8-#12 were added to get more information on temperature profiles. Insulation on the tubes carrying preheated air was found to be inadequate. New insulation was put on these tubes. Another problem was how to analyze the flue gas. An orifice meter was installed after the induced draft fan to measure the flow rate of the flue gas. A manometer was attached to the outlets of this orifice meter to supply information about the pressure drop. Pressure drop information can be used to calculate the average velocity of the flue gas in the duct and since the orifice opening dimensions are known, the volumetric flow rate of the flue gas can be calculated. The composition of the flue gas is monitored using Orsat analyzer which were installed before the induced draft fan.

A dry gas meter was also installed to monitor the flow rate of the natural gas. These steps were taken to aid in material balance and energy balance calculations.

CHAPTER IV

EXPERIMENTAL PROCEDURE AND RESULTS

This chapter is divided into four sections. The first section discuses the calibration of the necessary equipment. The second section discuses the testing of the air preheaters. The third section discuses the natural gas runs and the fourth section discuses the coal runs using Clovis Point coal.

Equipment Calibration

After system modifications, the second step in this research was to calibrate all the necessary equipment, before making runs with natural gas or coal.

The water rotameter was calibrated using a graduated cylinder. Water was collected in the cylinder and time was monitored using a stop watch. The flow rate of water was found to vary with time and it was impossible to keep a constant water flow rate. The calibration graph is shown in Figure 5.

Rotameters for the combustion air and the cooling air were calibrated using a wet test meter. The wet test meter had to be repaired prior to use. To make sure that the wet test meter was working properly, the rotameter for the

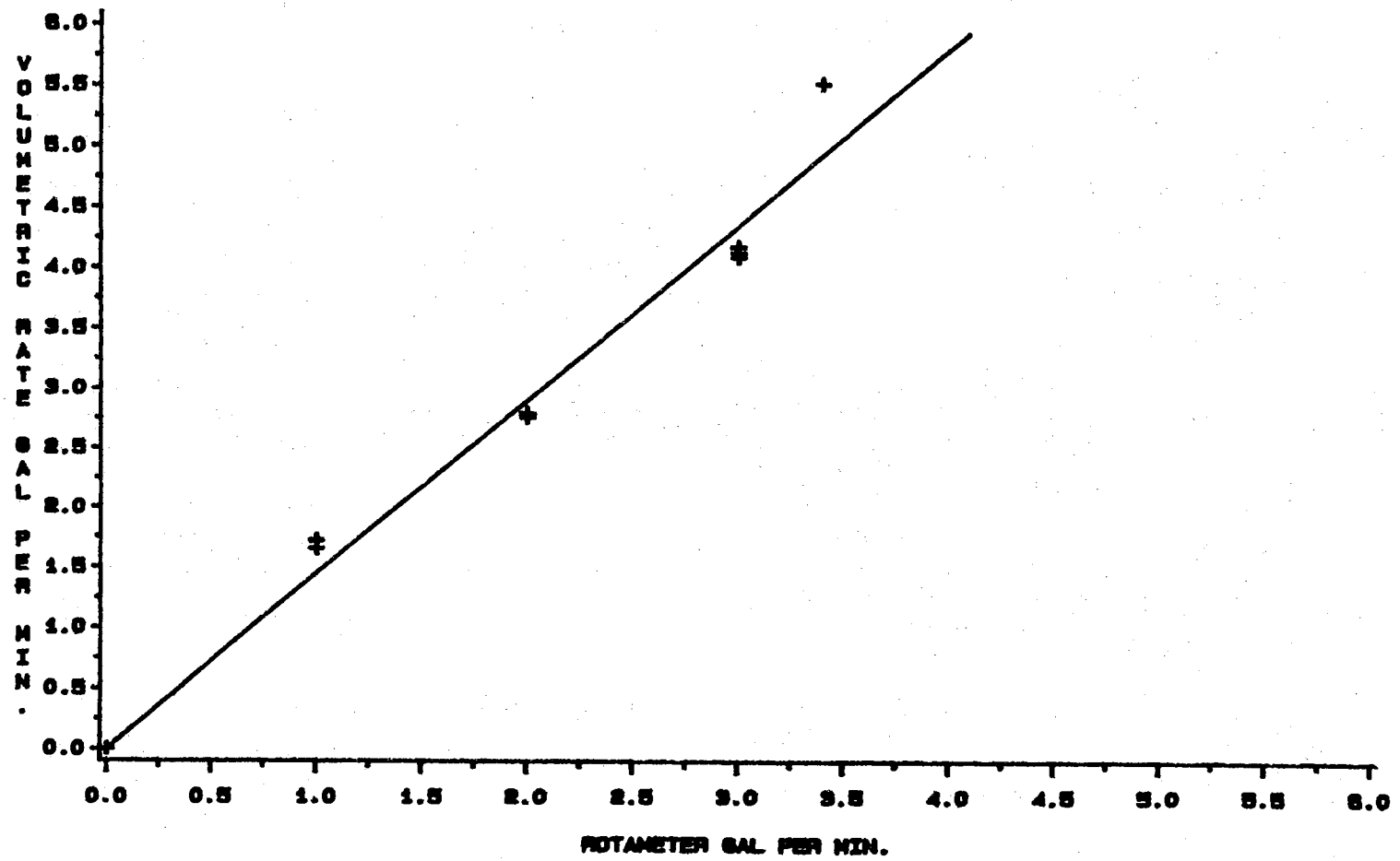

FIGURE 5. CALIBRATION OF ROTAMETER(WATER)

primary air was also calibrated using the dry gas meter. The data obtained from the wet test meter and the dry gas meter were found to be identical. The air flow rates varied with time. Another important finding was that whenever the main air compressor of the building was turned on, the air flow rates increased. Hence, making it impossible to maintain a completely constant air flow rate. The calibration graphs for the primary air, the secondary air and the tertiary air rotameters are shown in Figures 6-8, respectively. The rotameter for the cooling air was found to be very accurate hence there was no need for a calibration curve.

The coal feeder was calibrated using a balance and stop watch. Clovis Point coal with particles size of 5 mesh was used. The coal feeder was also checked for fluidized condition. The calibration curve is shown in Figure 9. The Orsat meters for flue gas analysis were also checked by feeding a mixture of carbon dioxide and oxygen gas of known composition. The Orsat meters were found to be accurate within 2%. The orifice meter located in the stack could not be calibrated for a number of reasons. First, it was impossible to get accurate results because of leakage around the furnace and second, the flow rate going through the orifice meter was controlled by the induced draft fan. Data for all the calibrations can be found in appendix A.

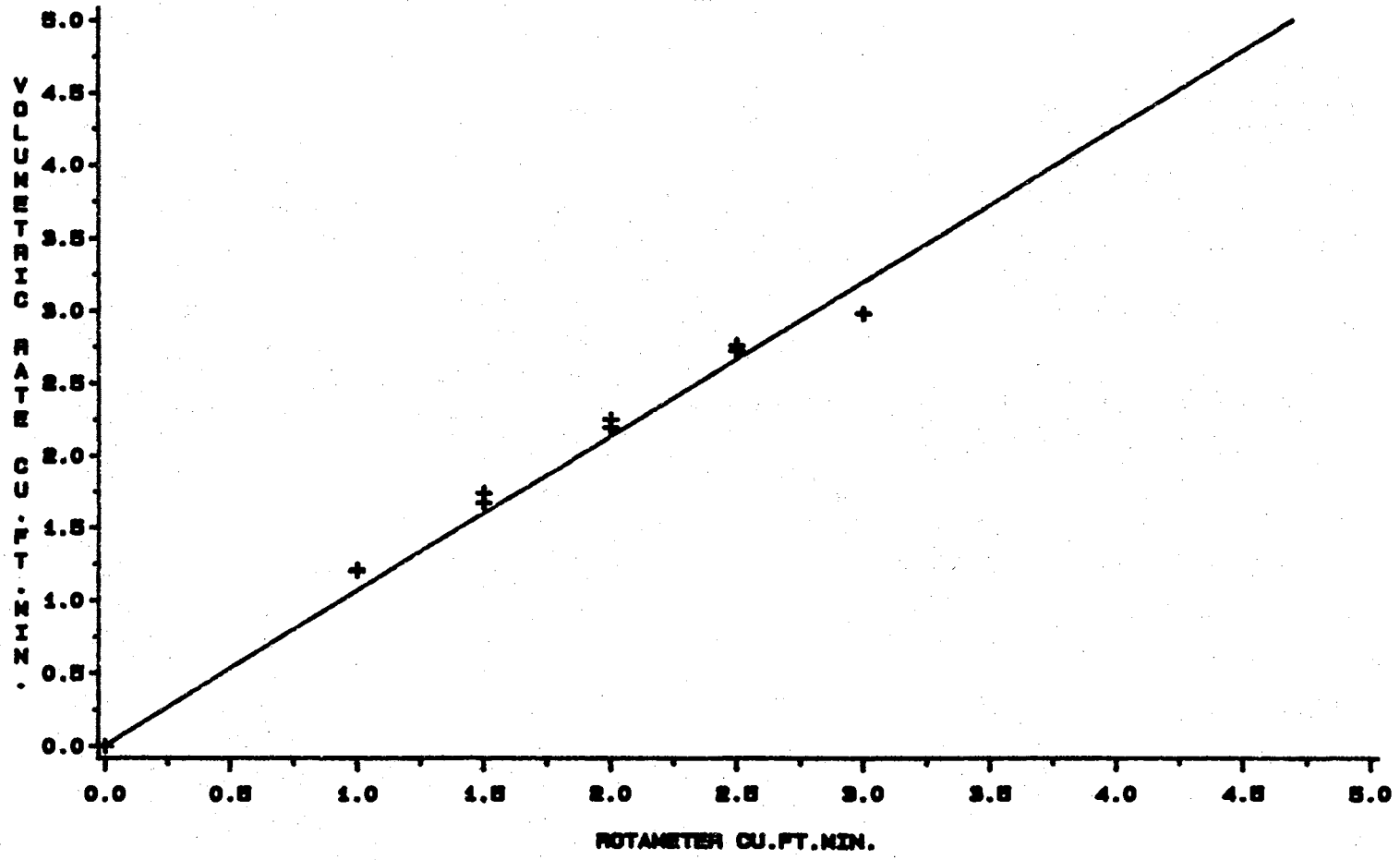

FIGURE 6. CALIBRATION OF ROTAMETER(PRIMARY AIR)

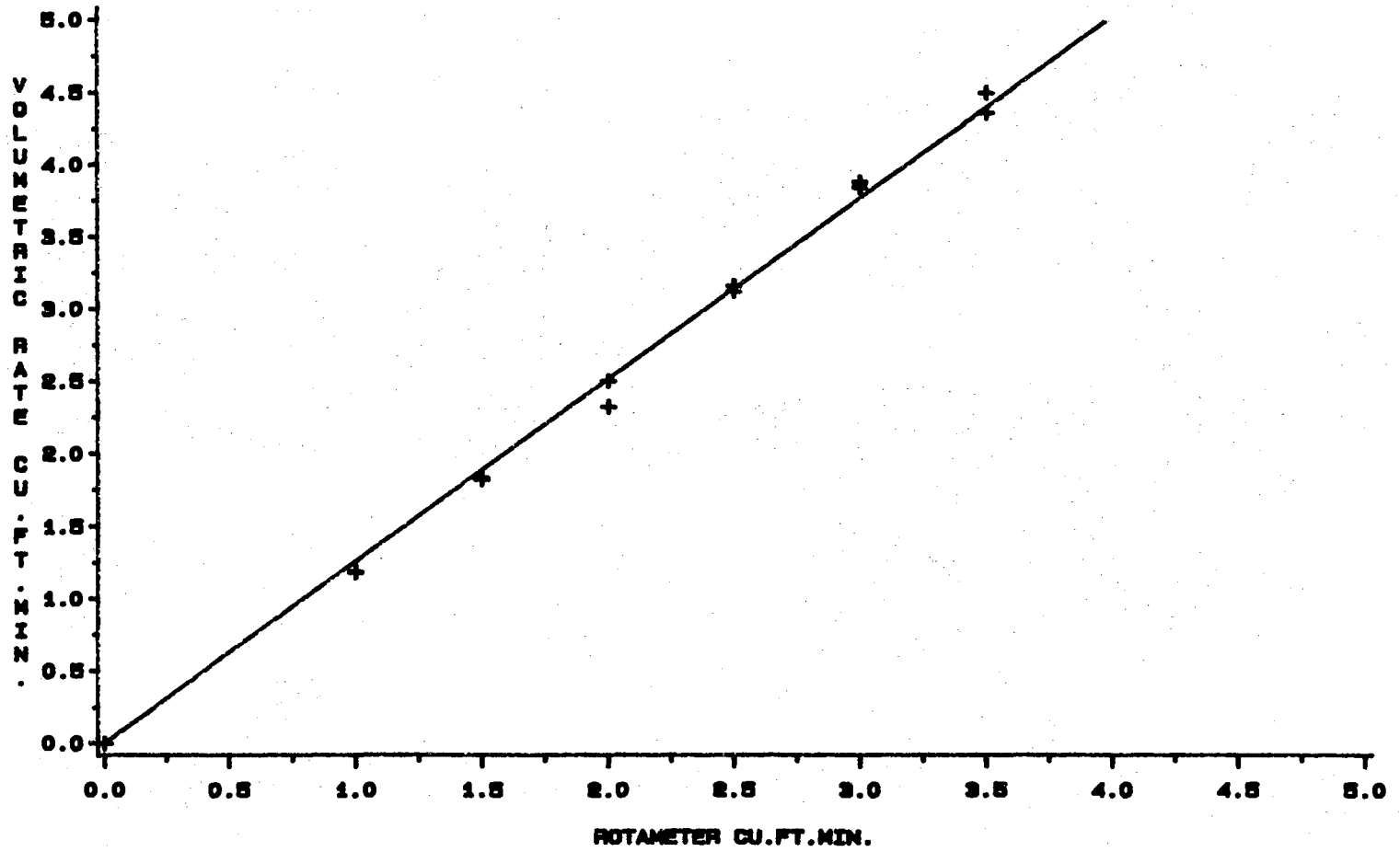

FIGURE 7. CALIBRATION OF ROTAMETER(SECONDARY AIR)

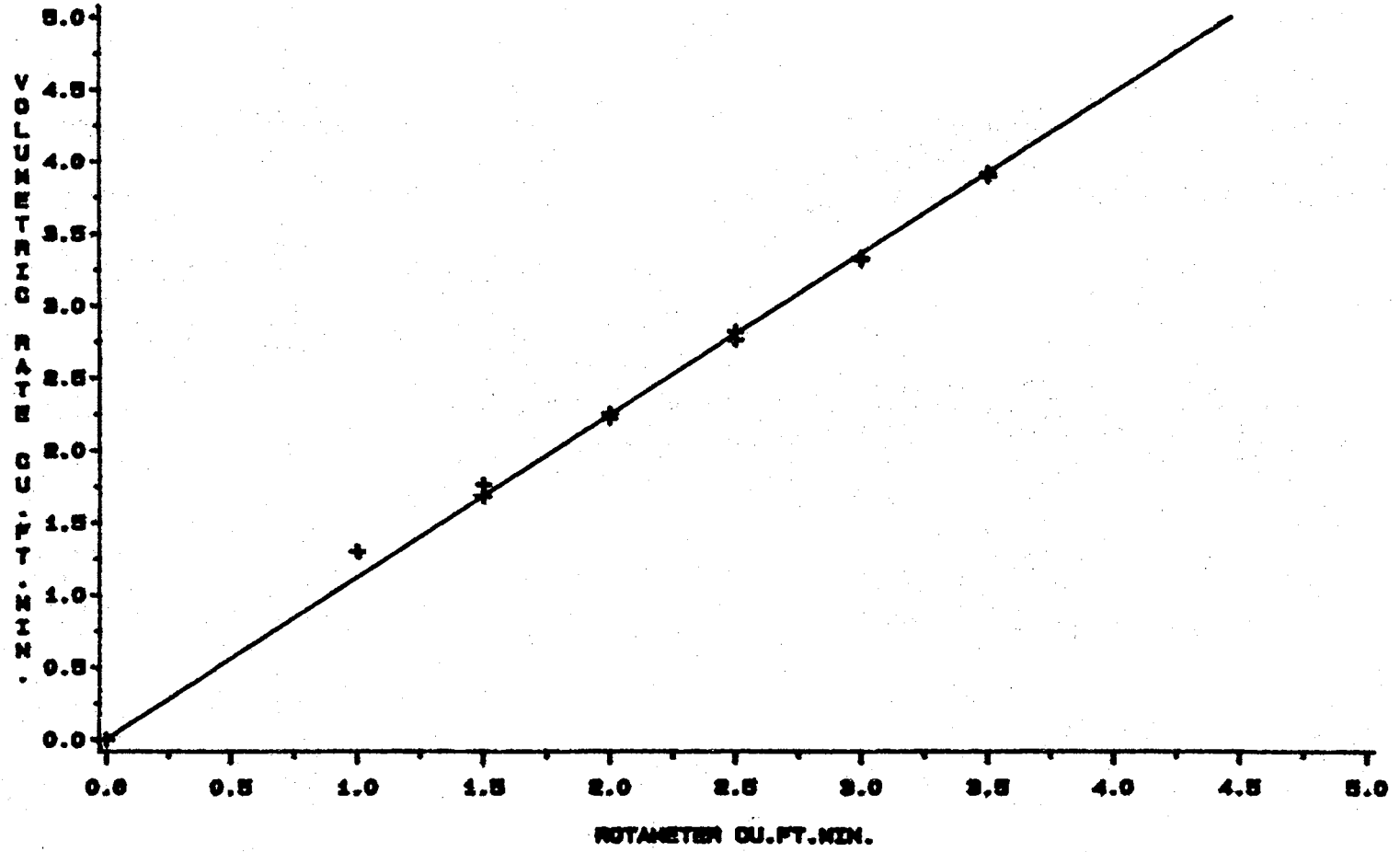

FIGURE 8. CALIBRATION OF ROTAMETER(TERTIARY AIR)

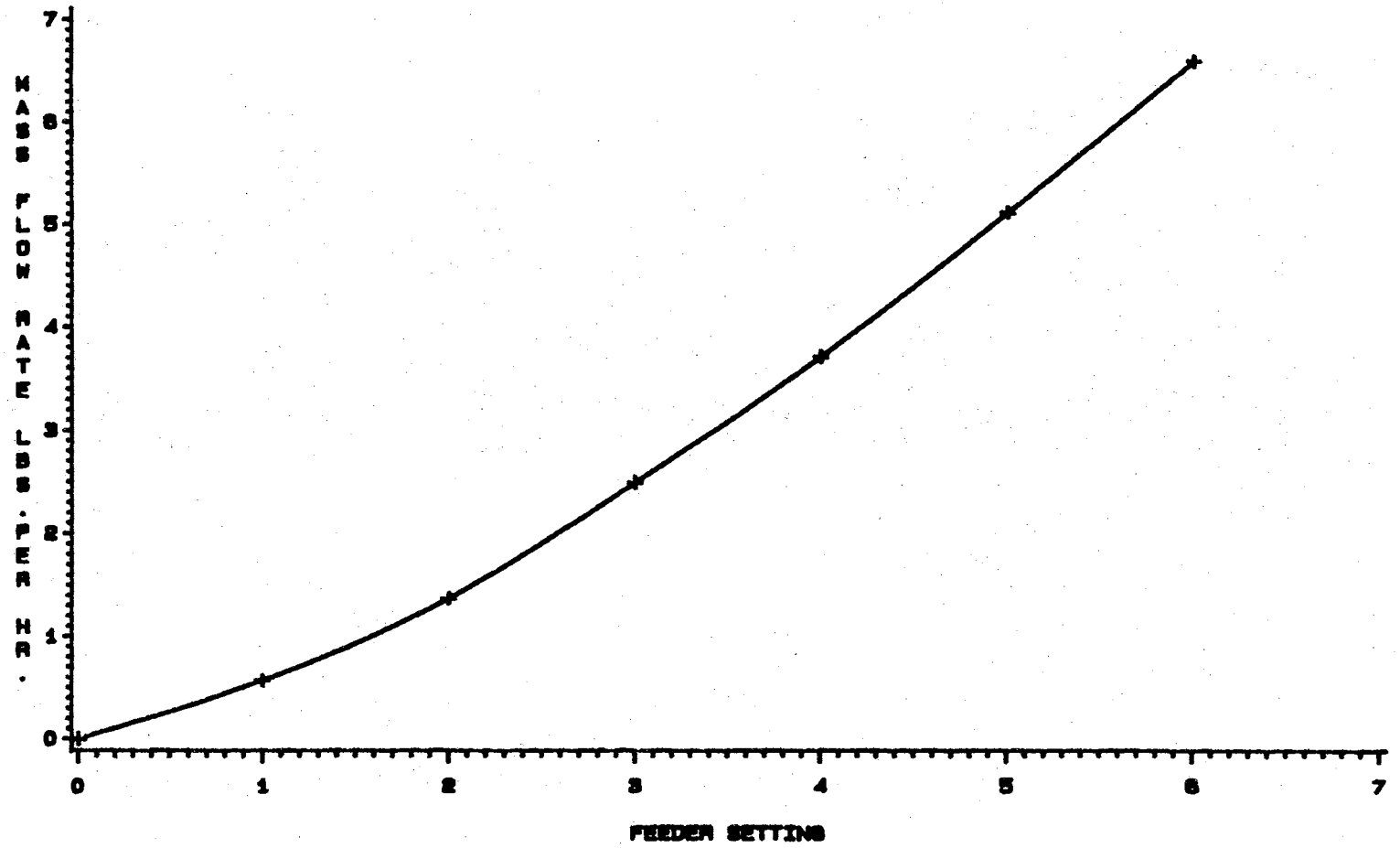

FIGURE 9. CALIBRATION OF COAL FEEDER

A manometer was used to measure the pressure inside the furnace when the induced draft fan was on. No readings could be obtained from this manometer.

Testing of Air Preheaters

After calibration of the necessary equipment, the preheaters for the secondary and the tertiary air were tested. Initially, the preheaters were operated for four hours with an inlet air flow rate of 2.5 c.f.m. The temperature of the secondary and the tertiary air reached 500°C. At this point the insulation that was used for covering the heaters started burning.

New insulation made of glass wool was wrapped around the preheaters. The addition of the new insulation made the preheaters very efficient at high temperatures. After making additional tests, the preheater for the tertiary air malfunctioned. It was replaced by a new heater. Another problem was discovered after running these preheaters for more than eight hours. At this time it was discovered that the electrical connections would not hold up. New electrical connections which would work under high temperature were replaced. During this process, the insulation was removed and replaced many times. Care must be taken when handling the insulation as it is made of glass wool and it can be very irritating to the skin. After making these corrections, the secondary and the

tertiary air preheated to 400°C were run in the furnace for 24 hours at a rate of 2.5 c.f.m. The temperature in the primary chamber went up to 80°C during this period. A spare preheater was built for emergency use.

Natural Gas Run

Test runs of the furnace were carried out using natural gas as the heat source. The basic procedure is described below.

The furnace was heated by using preheated secondary and tertiary air for twenty four hours. The temperature in the primary chamber was found to be 70°C. Initial calculations were done to calculate the amount of theoretical oxygen needed to burn the natural gas. It was found that these calculations were of little use when making an actual run. In an actual run the flow rates were varied until the combustion was supported in the furnace. At first, theoretical air flow rates and a minimum amount of gas were used but the flame in the primary chamber was not stable and could not be maintained for the reasons explained below. After trying many times to light the furnace using the theoretical amount of air and minimum amount of gas, the flow rates were adjusted to maintain a stable flame.

After the furnace was preheated by the secondary and the tertiary air, the tertiary air valve was shutdown and

the secondary air flow rate was dropped to 1 c.f.m. The primary air was turned on at 1 c.f.m. The induced draft fan was then turned on. This fan produced a negative pressure in the furnace which prevented the fire from coming out of the furnace when the sample ports were removed. The induced draft fan is controlled by a damper located in the stack.

Earlier the procedure stated by Shen Wang (1987) suggested that the natural gas should be fully opened and then the furnace should be lit by a spark from the ash clean out located at the bottom of the first chamber. From personal experience, it was concluded that this was a very unsafe procedure as the flame could flash out through the ash clean out port. Therefore, a modification was made in the ignition procedure. Using a long steel rod, a fire wick was placed in the primary chamber and then the natural gas was turned on. This was done because the wick could not be safely placed near the gas burner. Most of the time the natural gas accumulated in the chamber prior to ignition and as a result large flame was produced when the furnace was lit. This flame came out of the furnace through the sampling port. After ignition, the tertiary air was turned on at 1.5 c.f.m.

After completing the above steps enough time was given for the flame to stabilize in the primary chamber. Natural gas was then increased and simultaneously combustion air

was also increased by a small amount. The most delicate part of the ignition procedure occurs when the cleaning port was replaced. Any mishandling caused the fire to go out. The cleaning port was inserted back very slowly. Each time the port was inserted in, the air flow rate was adjusted by increasing it slowly and the induced draft fan was adjusted by opening the damper slightly. After making each change, ample time was given for the flame in the chamber to stabilize.

The temperature was monitored by 12 thermocoulpes located at positions described in chapter 4. After the cleaning port was replaced, the cooling air and water for the sampling ports were turned on. Flue gas was monitored by Orsat meters. These Orsat meters gave the relative percentage of carbon dioxide and oxygen in the flue gas. Natural gas was used until steady state temperature conditions were achieved.

The procedure stated above was modified from the old procedure for many reasons. The main reason being safety. Very high emphasis was placed on safety. In the beginning, 0.5 c.f.m. of natural gas and a theoretical amount of air needed were used. This procedure did not work because of the locations of the air inlets and the gas burners in the primary chamber. Combustion air came in at very high velocity and it blew out the flame when the flow rate of natural gas was not strong enough. Sheng Wang (1987)

suggested using natural gas at its full capacity. The problem was resolved by using the minimum amount of natural gas needed to keep the flame alive which was found to be around 1.5 c.f.m. This was also done to avoid incomplete combustion as this would lower the temperature in the primary chamber.

Before making the first run, the furnace was lit several times for short periods to observe the effect of different factors on the flame in the primary chamber. Several observations were made. The induced draft fan was essential for stable combustion. The flame could not be maintained without using the fan after the cleaning port was replaced in the furnace. Care must be taken when replacing the cleaning port. Any changes in the air flow rates, in the natural gas flow rate or in the damper controlling the induced draft fan, had to be very gradual. Even when the port was fully closed, the induced draft fan drew air in from the outside through different locations in the furnace. This air leakage must be considered when making calculations for material balance.

Another important discovery was that as the furnace got hotter, it was easier to light up the furnace. Initially preheated air was used to heat the furnace before lighting it. However, after many ignition attempts, it was concluded that the furnace itself becomes very hot by the different attempts that are made to light it. Hence it was

not necessary to preheat the furnace using heated air.

Coal Run

Before coal could be used to operate the furnace, the furnace was heated to a temperature of as high as possible (around 1000°C) using natural gas and by following the procedure outlined above. After the furnace had reached steady state conditions using natural gas, coal was introduced using the coal feeder. The primary air carried coal into the coal burner and the furnace. To have an efficient flow of coal, the coal particles were ground to 20 mesh. Once the coal flow was turned on, the natural gas was cut off.

Inside Inspection of the Furnace

After each long run, the front door of the furnace was taken off. The procedure for removing the door requires a lot of effort and caution as the door itself weighs over 800 lbs. The first step was to remove the three thermocouples that go into the furnace through the front door. This is a very delicate process, as any mishandling of these thermocouples would have broken the ceramic covering which goes over the thermocouple wires. The second step was to loosen the 14 bolts that connect the door to the furnace. The door rests on cement bricks. After loosening the bolts, a hydraulic jack was placed

beneath the door and the supporting bricks were then removed. All the bolts were taken out and the door was removed. This procedure requires at least two people. Replacing the door requires more effort since the door must be in perfect alignment with the furnace before the bolts can be replaced and it requires at least three people. Once the bolts were replaced, bricks were placed under the furnace and the hydraulic jack was removed.

Run No.1 using Natural Gas

The first successful run was carried out using 1.5 c.f.m. of natural gas, 2.15 c.f.m. of primary air, 2.35 c.f.m. of secondary air and 2.75 c.f.m. of tertiary air. The same experimental procedure was followed as described previously. The furnace was lit after many attempts. The clean out port was inserted back when the temperature in the primary chamber reached 650°C. This was the first run and the impression was that it would take around six hours to achieve steady state. However temperature readings taken after five hours were thought to be at steady state. It was found from later runs that it takes longer time to achieve steady state conditions. The temperature profiles as a function of time are shown in Table V. The temperature in the primary chamber after five hour was 793°C. One of the objectives of this run was to determine the temperature of the furnace without any heat

TABLE V

TEMPERATURE PROFILES
(CENTIGRADE)

Thermocouple #	Time(Hr.) 3	5	6.5	7	8.5
1	781	793	748	749	759
2	644	689	614	623	651
3	468	493	438	445	465
4	129	140	143	147	157
5	220	236	223	227	239
6	380	390	382	373	364
7	363	370	362	356	360
8	-	-	22	22	23
9	-	-	110	110	117
10	-	-	169	173	182
11	-	-	100	106	110

exchangers operating. This temperature was found to be 797°C. After finding this temperature the cooling air and the water were turned on after five and a half hours. This decreased the temperatures in the furnace. Later on, from other runs it was concluded that the operational adiabatic temperature was around 1100°C. Operating the furnace under these temperature conditions, without cooling air, would have damaged the stack and the induced draft fan. Therefore, the idea of finding the furnace temperature without heat exchanger was discarded. Cooling air was ran for three hours. From Table V, it can be seen that there was a gradual increase in the temperatures in the furnace until the cooling air was turned on. This caused an original decrease in the temperatures but once the conditions were stabilized, the temperatures in the furnace started to increase. Flue gas was analyzed after eight and a half hours using Orsat meters. The flue gas contained 3% CO_2 and 13% O_2. This run lasted for eight and a half hours. From this run, it was proven that the furnace was operative using natural gas. The air cooled heat exchangers were found to work efficiently. From the temperature profile of thermocouple #8, it was clear that there was not much heat transfer between the water going in the tubes of the sampling port and the inside surrounding of the primary chamber.

Run No.2 using Natural Gas

There were few changes introduced in the second run. The primary objective of this run was to replicate run number one. The tertiary air flow rate was decreased to 2.36 c.f.m. The cooling air and the water were turned on from the very beginning of this run. Unlike, the first run where there was a drop in temperatures when the cooling air and the water were turned on, the temperature gradually increased in this run except for the 11th hour. An interesting observation came when the cleaning port block was replaced in the furnace. All temperature zones except for the primary chamber showed an initial slight decrease followed by an expected increase. Another important observation was that after 11 hours, there was a sudden increase in the flue gas temperature.

The temperature profile for each thermocouple is shown in Figures 10-18. Period A in these figures represent temperature profiles before there was an increase in the flue gas temperature and Period B represents temperature profiles after there was an increase in the flue gas temperature. Figure 10 shows the temperature profile of the primary chamber. From this graph, it is seen that the temperature increased relatively fast for the first four hours. It increased from 670°C to 757°C in the first four hours and then it only increased 10°C in the next seven

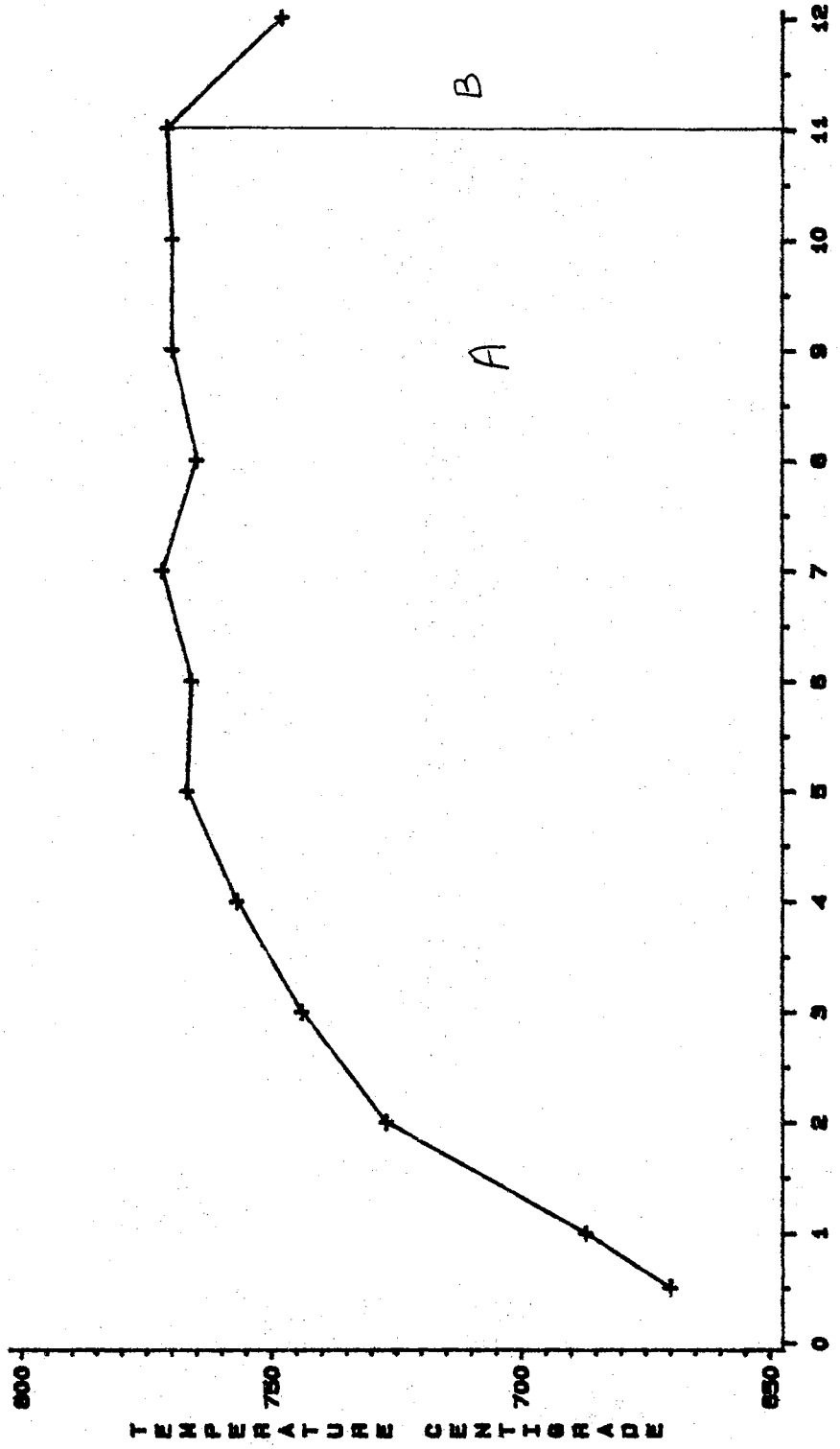

FIGURE 10. TEMPERATURE PROFILE NO.1 PRIMARY CHAMBER(RUN #2)

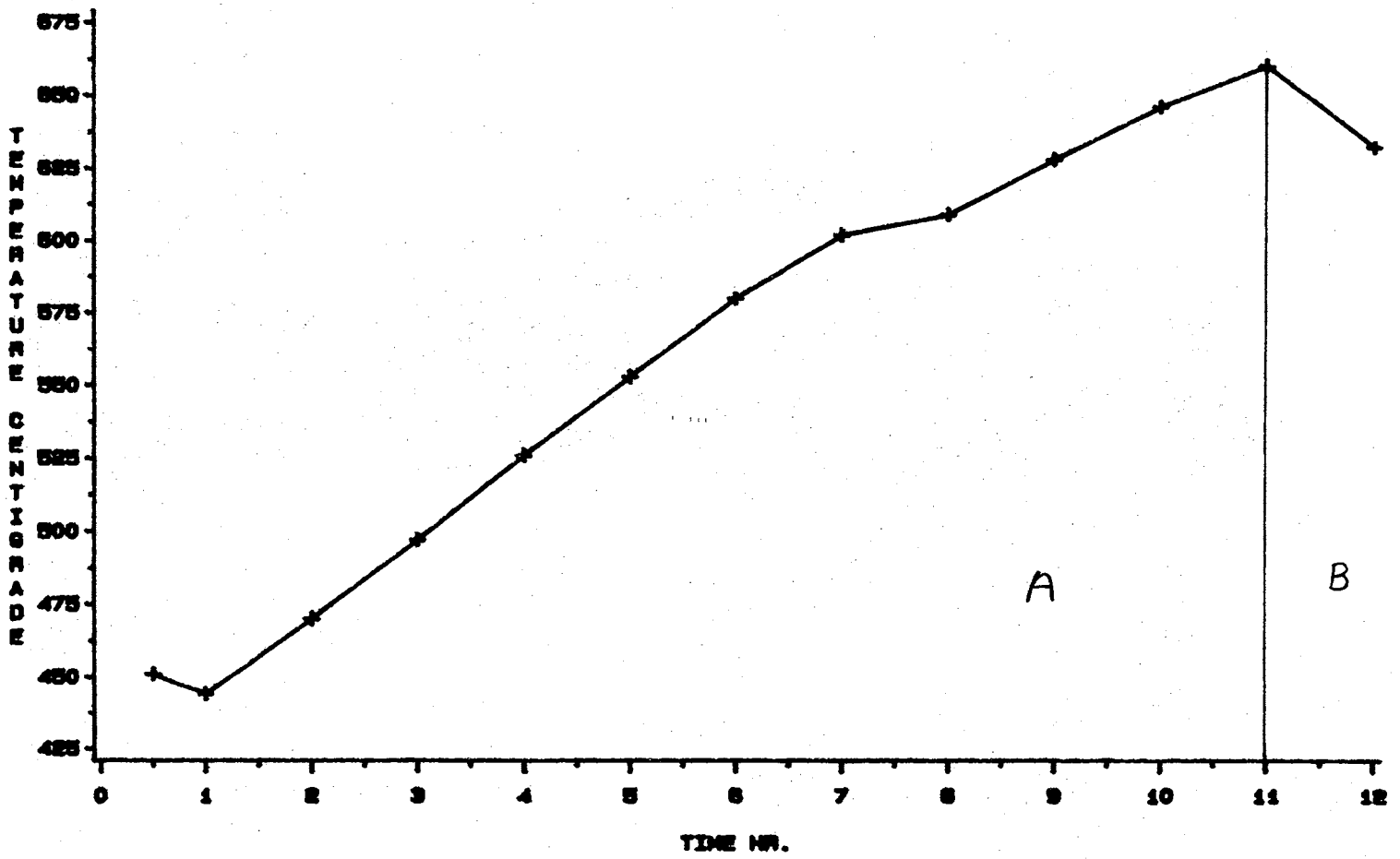

FIGURE 11. TEMPERATURE PROFILE NO.2 THROAT(RUN #2)

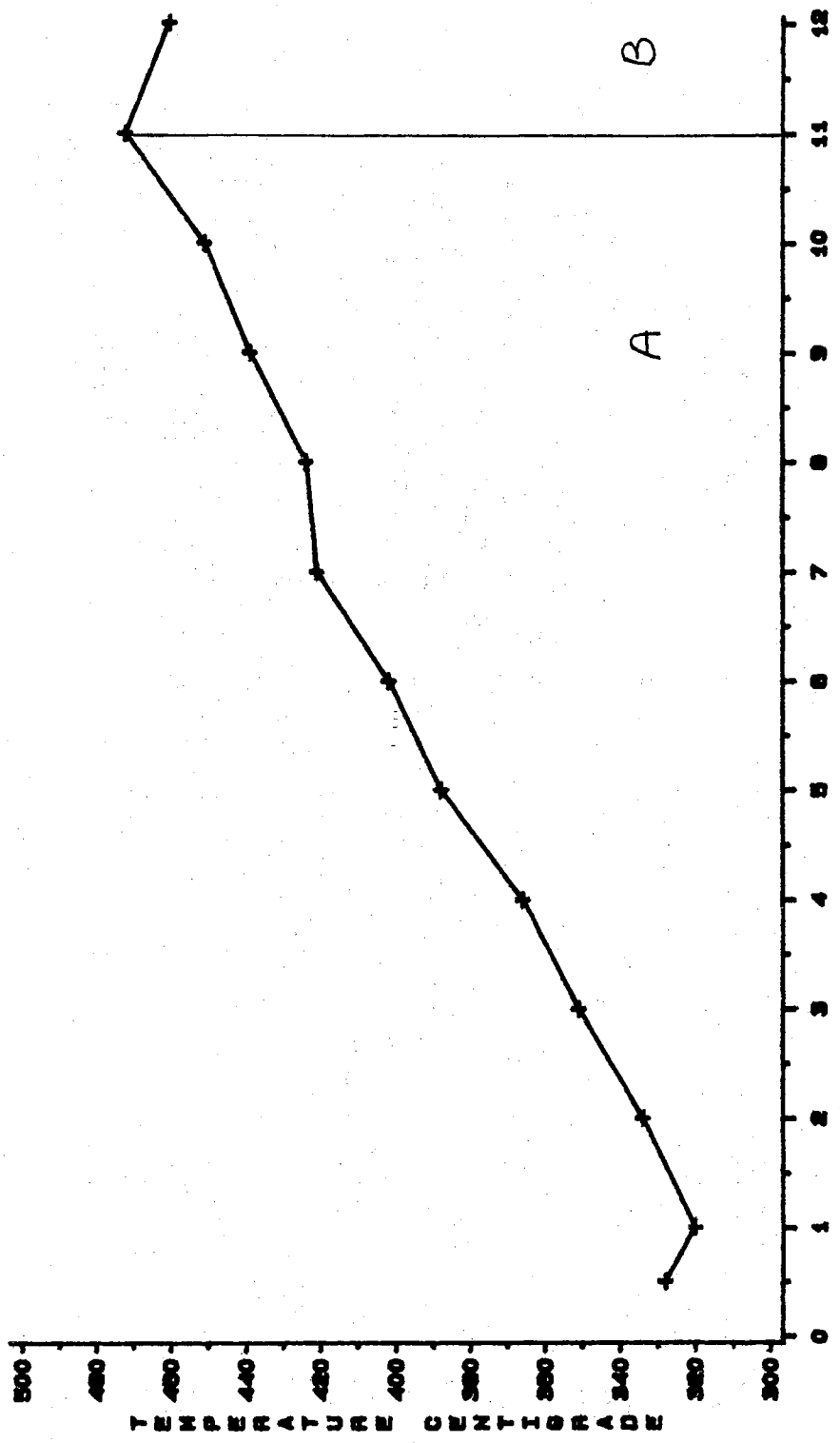

FIGURE 12. TEMPERATURE PROFILE NO.3 SECONDARY CHAMBER(RUN #2)

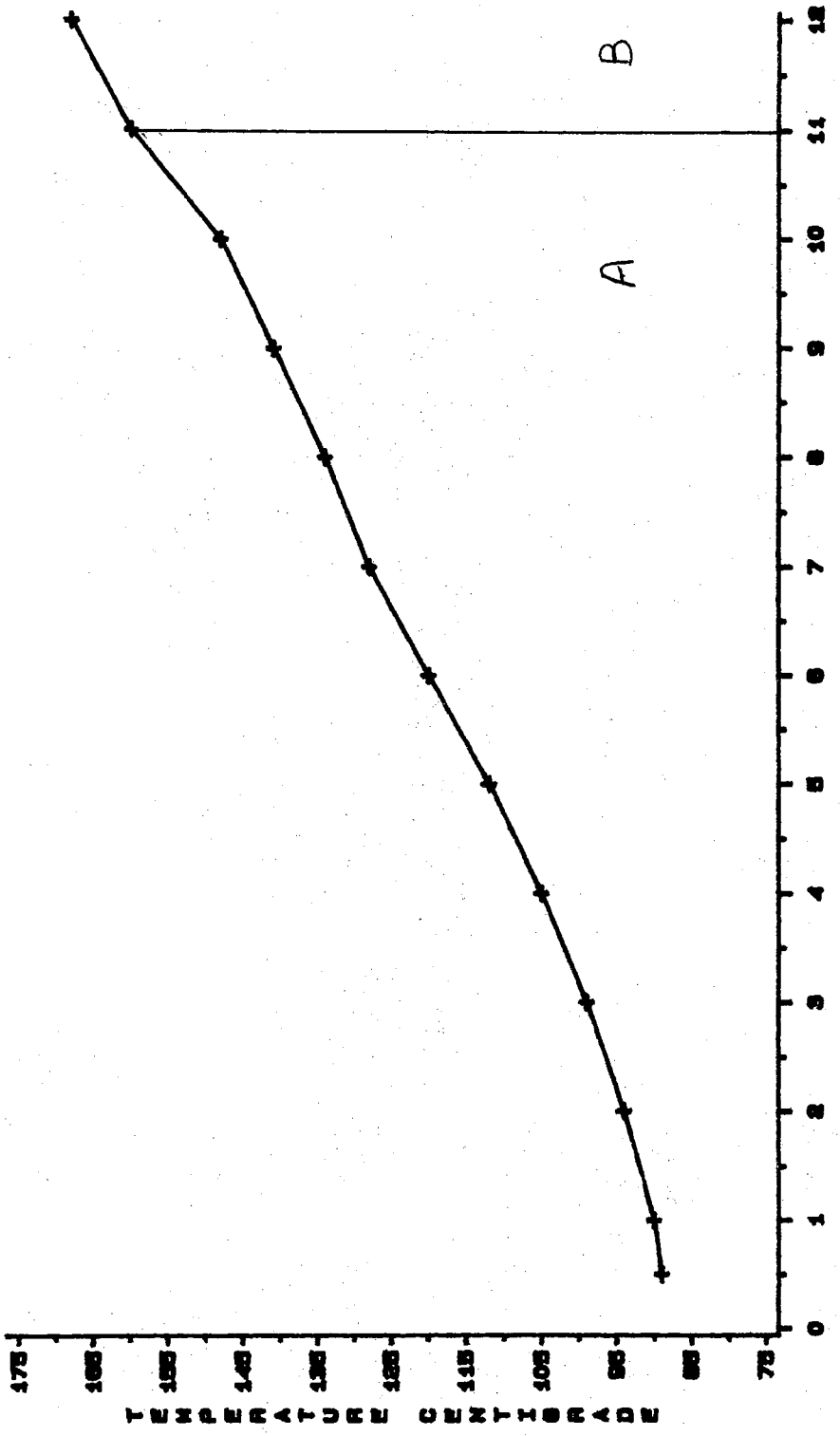

FIGURE 13. TEMPERATURE PROFILE NO.4 SECONDARY CHAMBER WALL(RUN #2)

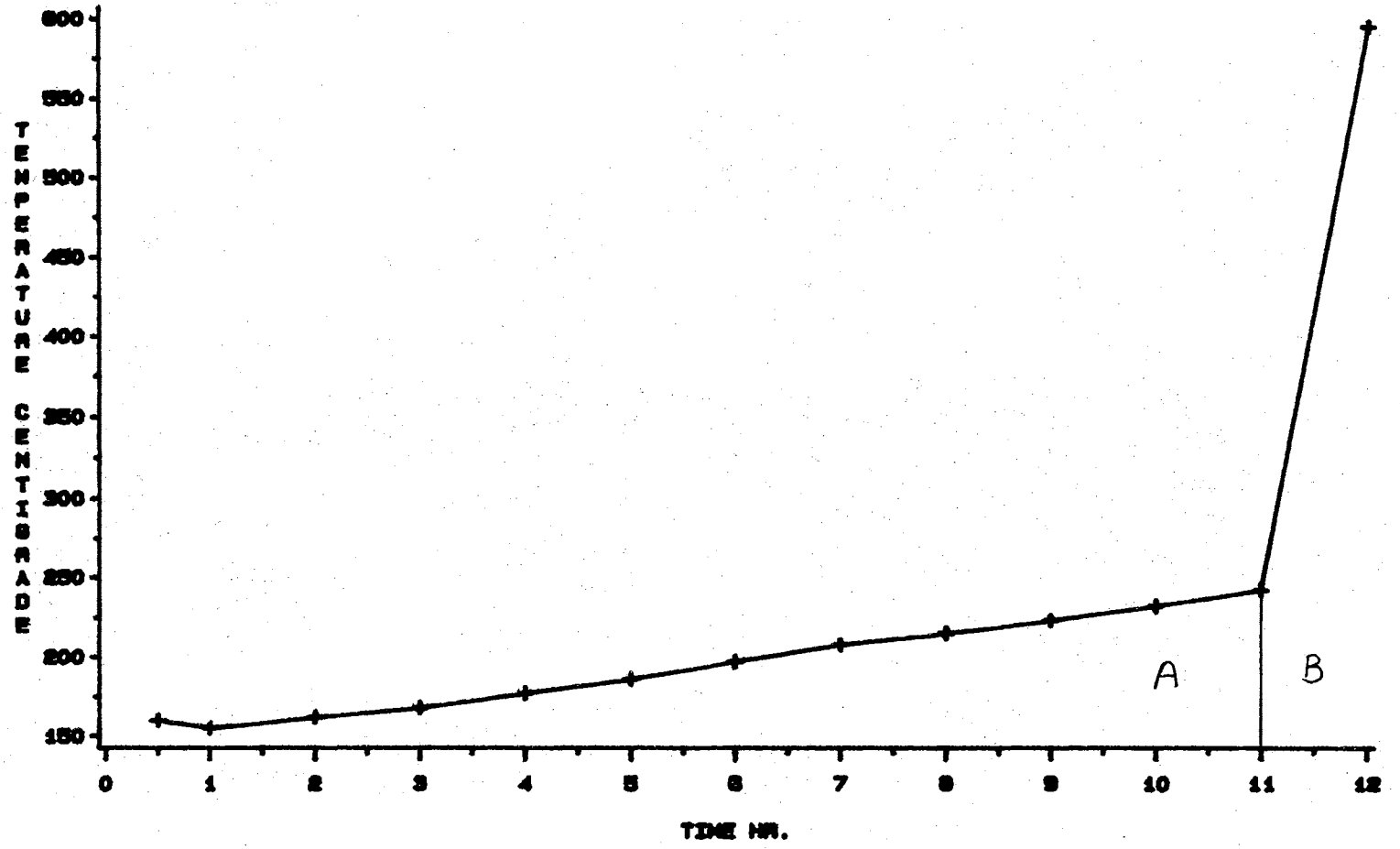

FIGURE 14. TEMPERATURE PROFILE NO.5 FLUE GAS(RUN #2)

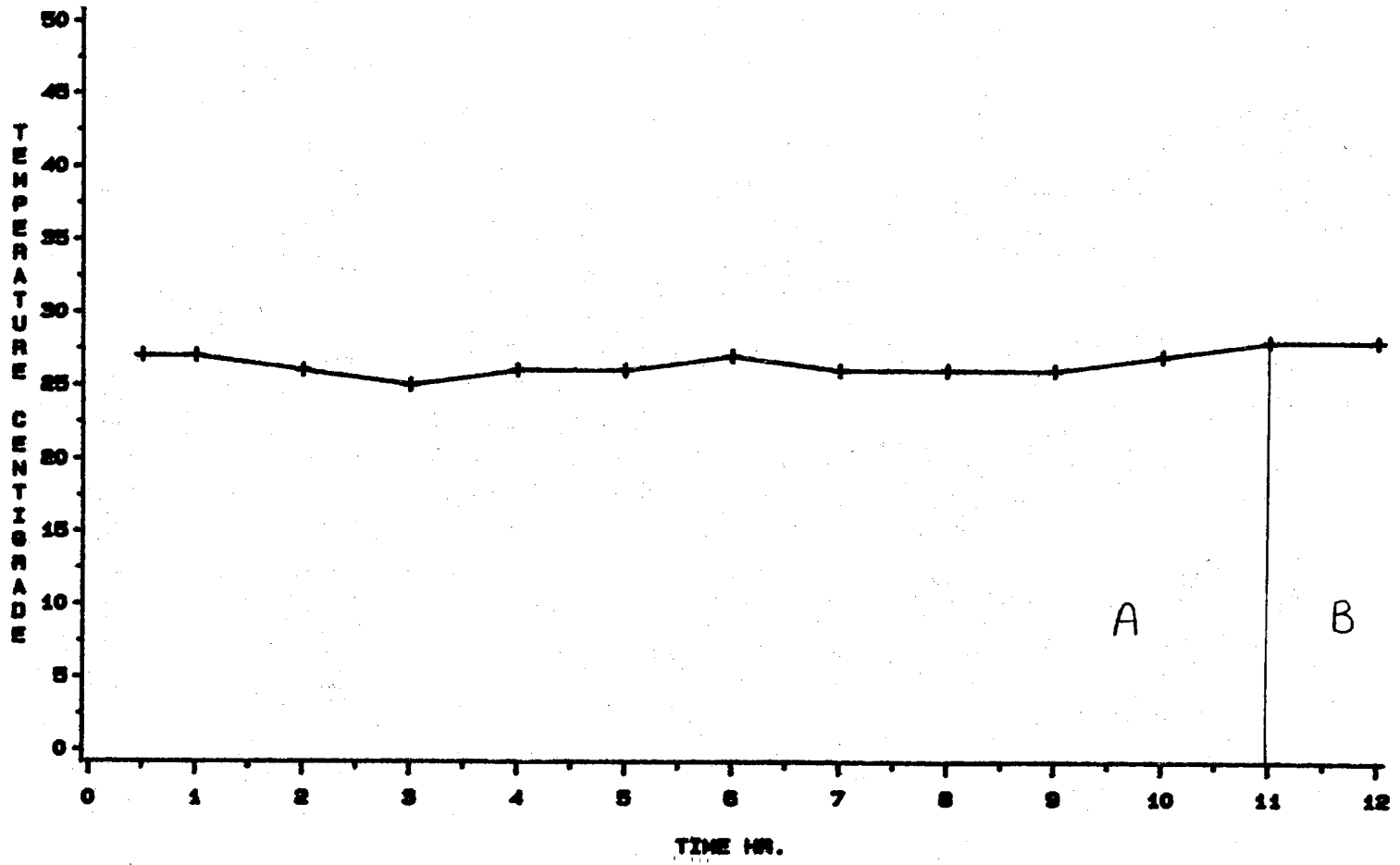

FIGURE 15. TEMPERATURE PROFILE NO.8 SAMPLING PORT WATER(RUN #2)

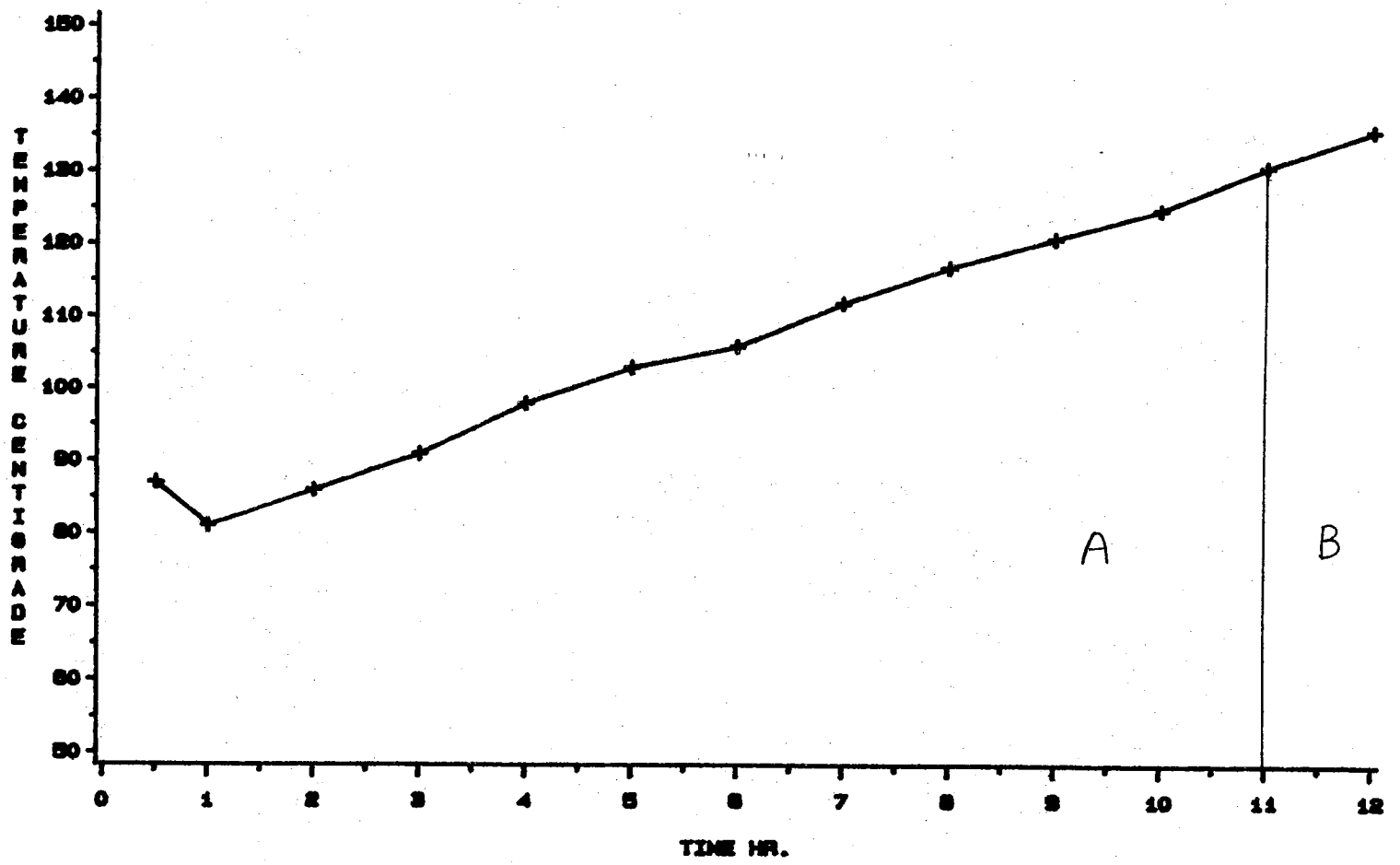

FIGURE 16. TEMPERATURE PROFILE NO.9 AIR HEAT EXCHANGER #1(RUN #2)

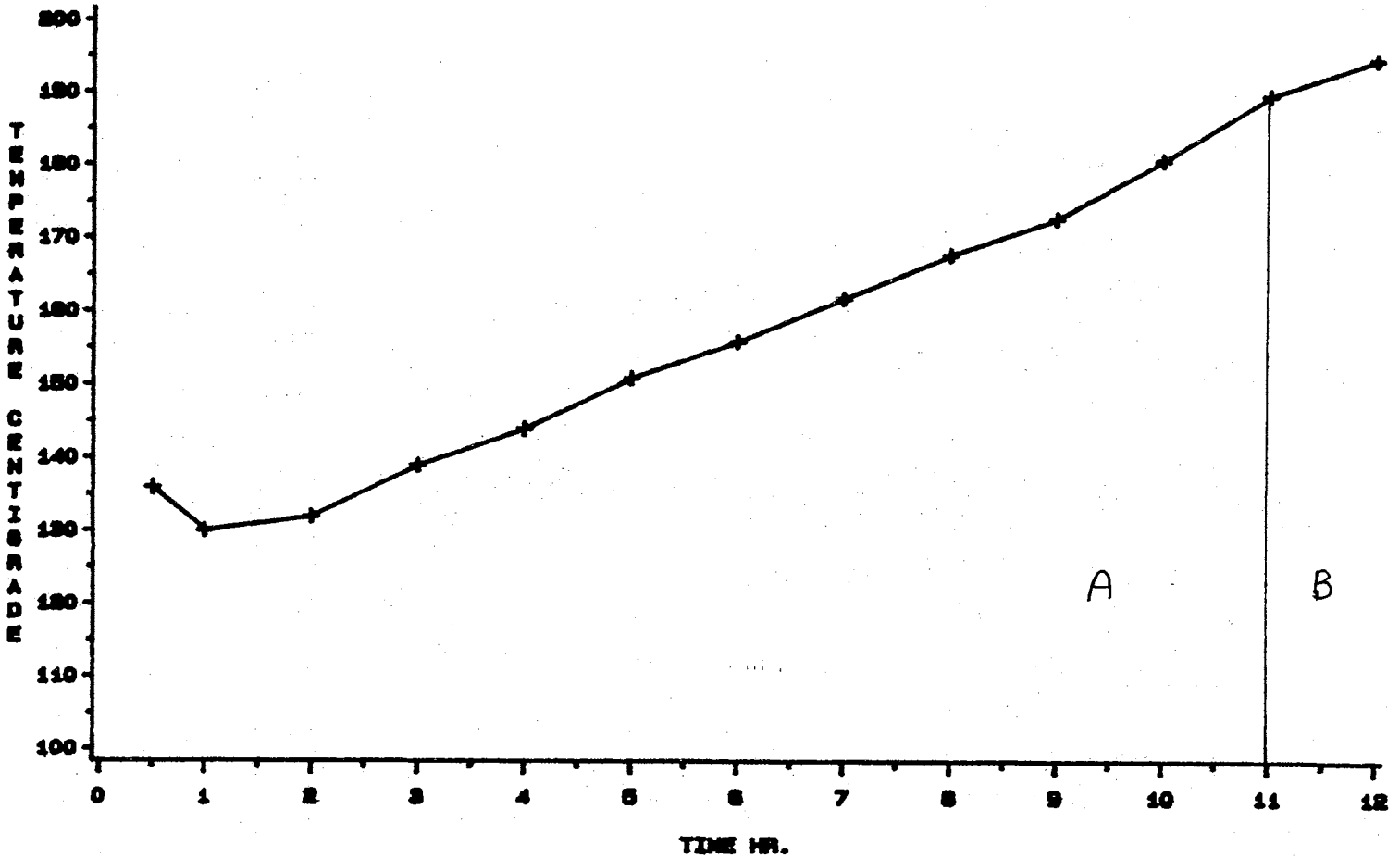

FIGURE 17. TEMPERATURE PROFILE NO.10 AIR HEAT EXCHANGER #2(RUN #2)

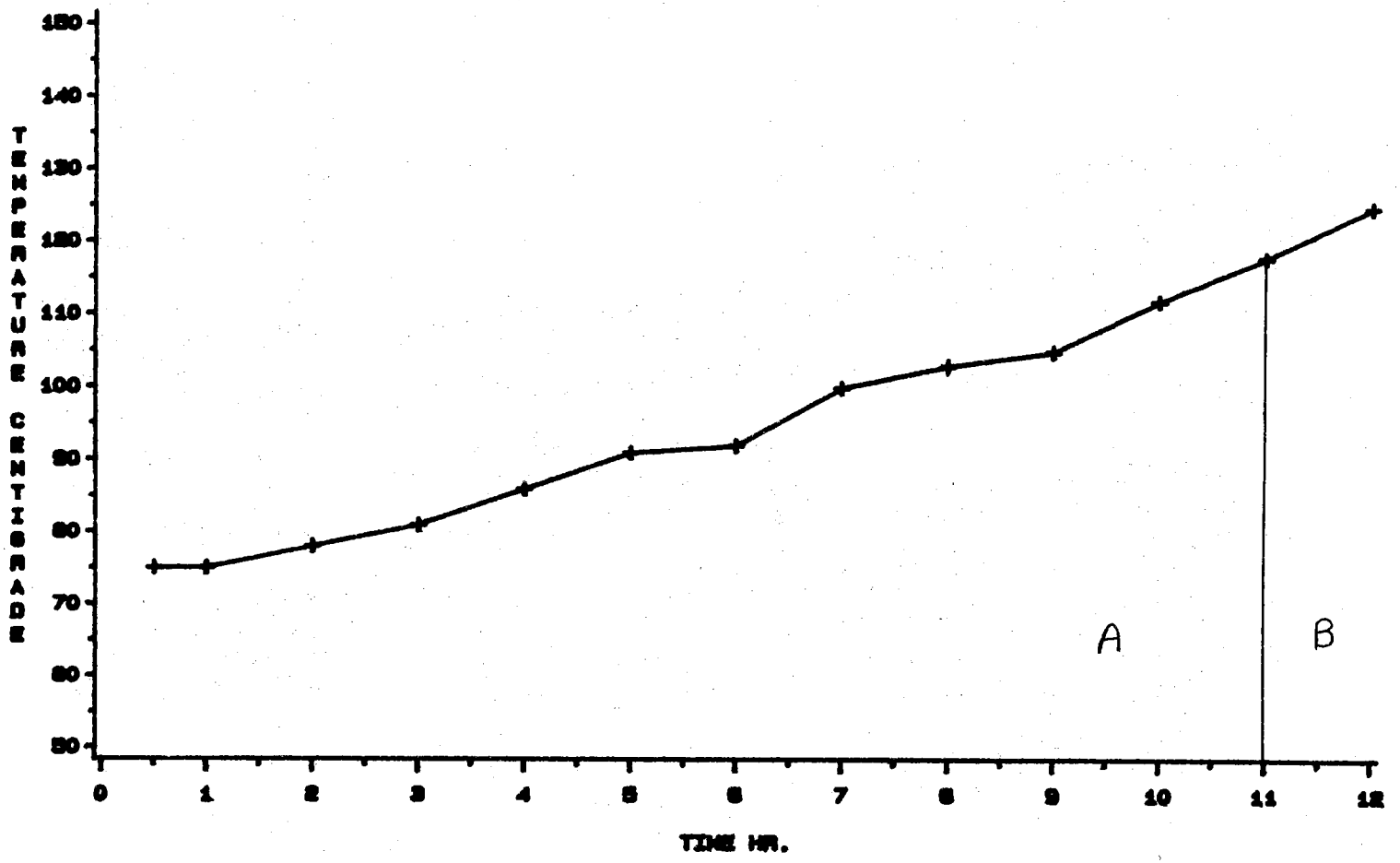

FIGURE 18. TEMPERATURE PROFILE NO.11 AIR HEAT EXCHANGER #3(RUN #2)

hours. Some time after eleven hours the temperature in the primary chamber decreased as the flue gas temperature increased. Figure 11 shows the temperature profile at the throat that connects the primary chamber and the secondary chamber. Figure 12 shows the temperature profile of the upper section of the secondary chamber after the first air cooled heat exchanger. Both curves show the similar pattern. In the early stage after the cleaning port was replaced, there was a slight temperature decrease in both locations. Both temperatures then increased till after 11 hours, after which both decreased. Figure 13 shows the temperature profile of the bottom wall of the secondary chamber. Originally this thermocouple was installed to measure the temperature of the lower section in the secondary chamber. However due to an installation error, it actually measured the temperature of the lower front wall in the secondary chamber. The wall temperature increased gradually with time and was not affected by the increase in the flue gas temperature. Figure 14 shows the temperature profile of the flue gas. After eleven hours there was a very sharp increase in the temperature of the flue gas. Figure 15 shows the temperature profile of water coming out of the sampling port in the primary chamber. As mentioned previously, there seemed to be little heat transfer between the water and the primary chamber. This could be due to the fact that the flow rate of water was

very high in the sampling port although a minimum amount of water was used. Figures 16-18 show the temperature profiles of the air coming out of the three air cooled heat exchangers in the secondary chamber. In the beginning stage, air coming out of the top two heat exchangers show the same temperature drop as in the case of the secondary chamber and the throat. Apart from this, these graphs show gradual increase in the temperature all the way till the end of the run and they show no effects of the increase in the flue gas temperature.

The composition of the flue gas is shown in Figure 19. As expected, with more time more CO_2 and less O_2 were found in the flue gas implying that the combustion efficiency increased with time as the furnace approached steady state. This run was cut short because of a fear that the sudden increase in the temperature of the flue gas would damage the stack and the induced draft fan. The data for this run can be found in appendix A.

At the end of this run the equipment was inspected for damage, the only thing damaged was the brick wall of the sampling port in the primary chamber. It had cracks in it. In future runs, it would be seen if the same situation repeats itself or not.

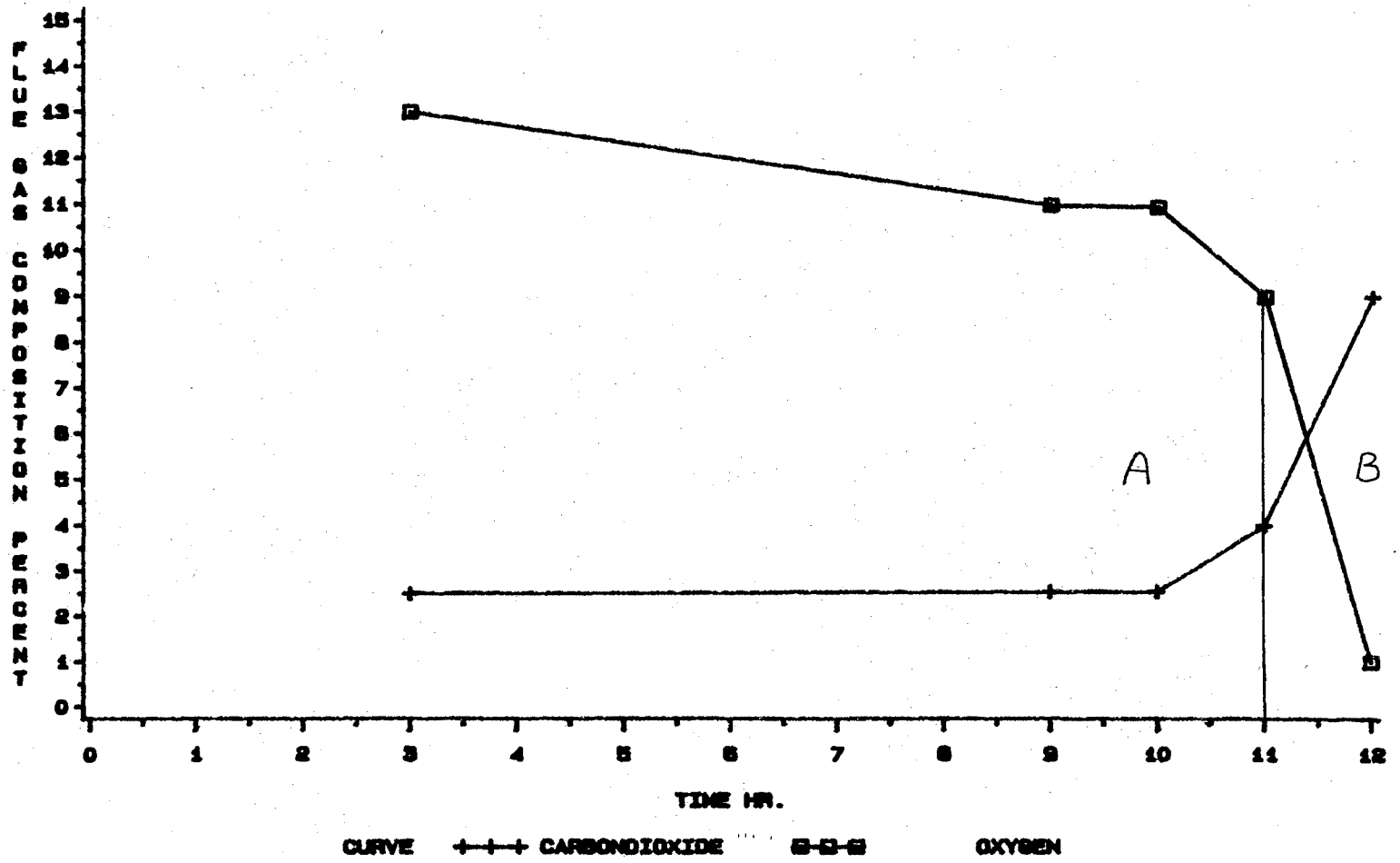

FIGURE 19. FLUE GAS COMPOSITION(RUN #2)

Run No.3 using Natural Gas

In this run, one major change was made. The damper controlling the induced draft fan was only open one quarter of the maximum. The data for this run is provided in appendix A. The temperature profiles were similar to the first two runs but the temperatures did not rise as high as in the first two runs especially in the primary chamber. The flame went out the end of four and a half hours. It was concluded from this run that the damper should be left open all the way when making a run to get a stable flame in the furnace.

At the end of this run the sampling port tubes, which carry water through the sampling port in the primary chamber broke from there joints. No damage occurred in the furnace as this problem was detected as soon as it developed and the run was aborted.

Run No.4 using Natural Gas

This was a very important run as it provided a great deal of useful information. All the flow rates were kept same as in the previous runs except the tertiary air which was increased to 2.75 c.f.m. The reason for this change was that uptill this point there was no standard way to light the furnace. It was just a matter of trying different combinations to determine a workable set of

conditions. In this run the damper on the induced draft fan was set wide open from the very beginning.

The main purpose of this run was to test burn the furnace for a very long period using natural gas to determine steady state conditions. Since the sampling port heat exchanger in the primary chamber had broken in run number 3. There was no water flow through the sampling port. Temperature profiles for different sections of the furnace are shown in Figures 20-27.

Period A in these figures represents the time before there was a sharp increase in the flue gas temperature. This phenomena occurred after eight hours. During this period the same patterns were observed in temperature profiles as in previous runs. In the primary chamber, the temperature increased from 618°C to 876°C during period A as shown in Figure 20. Temperatures in the throat and the upper section of the secondary chamber behaved as expected, first they decreased and then they gradually increased till the end of period A as shown in Figure 21 and Figure 22. Figure 23 shows the temperature profile of the lower wall of the secondary chamber. The temperature increased gradually during this period. A similar pattern is shown in Figure 24 for the flue gas for period A. In this run there was a momentary drop in temperatures of air coming out of all three heat exchangers when the cleaning port was replaced unlike the second run where the temperature drop

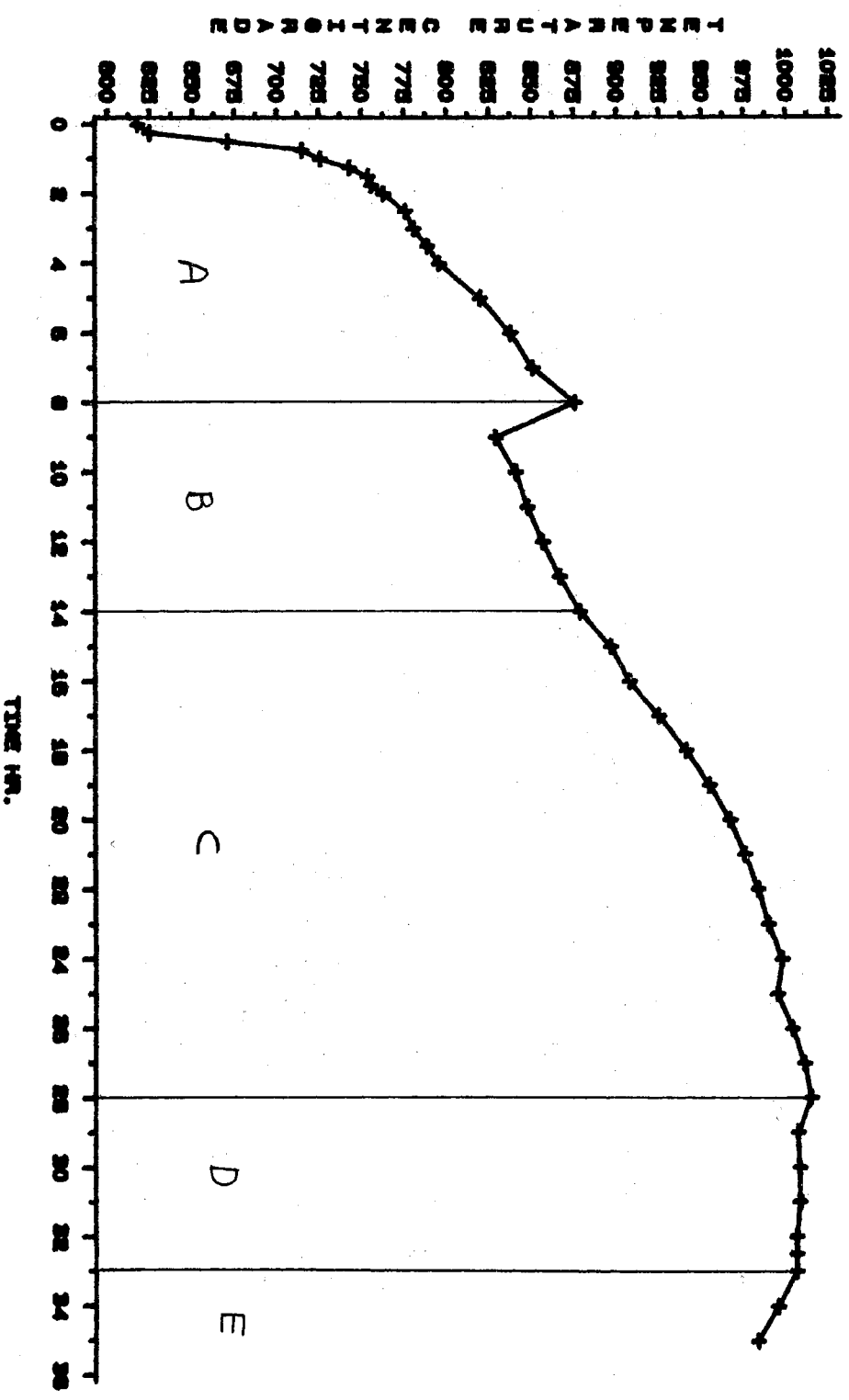

FIGURE 20. TEMPERATURE PROFILE NO.1 PRIMARY CHAMBER(RUN #4)

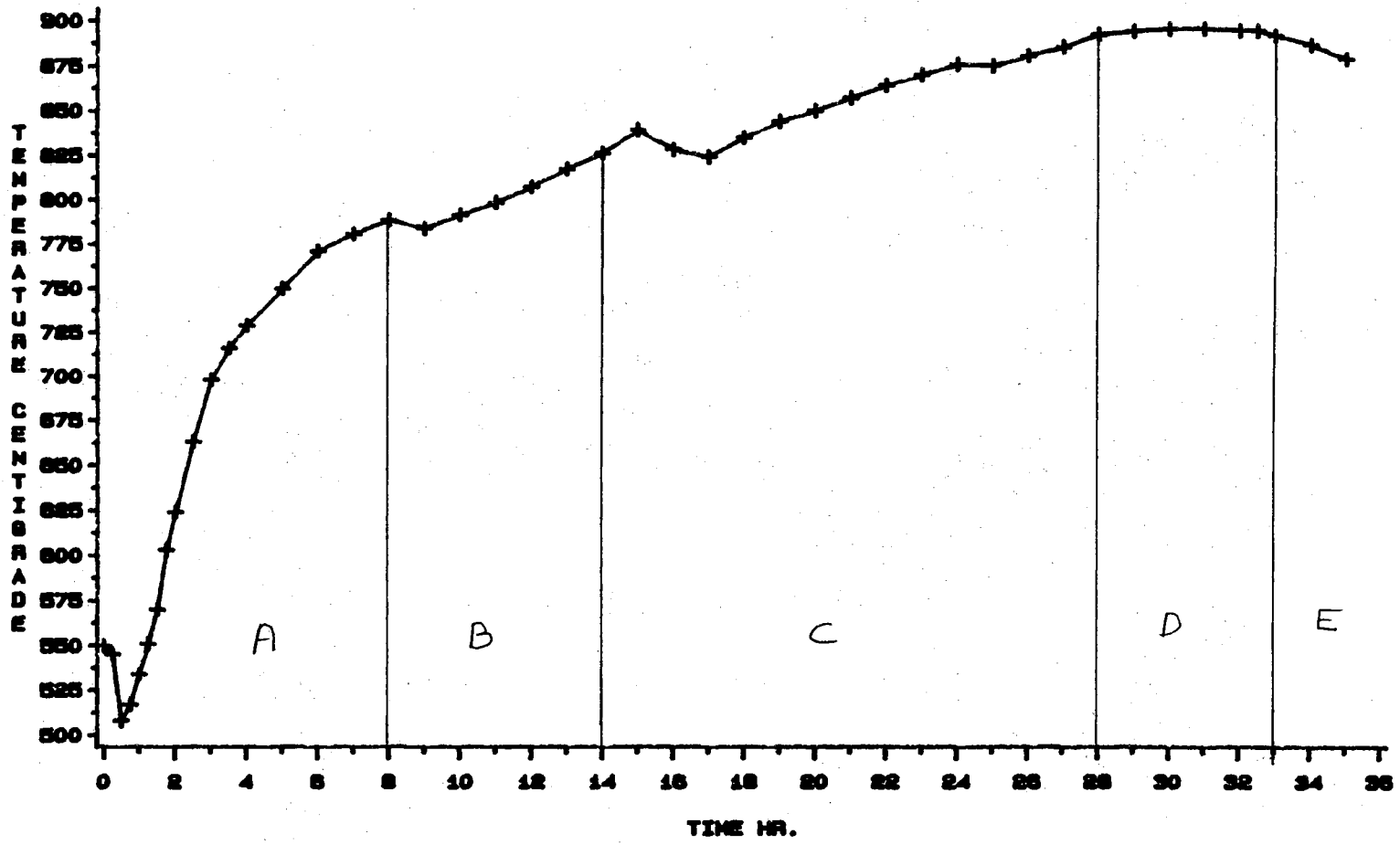

FIGURE 21. TEMPERATURE PROFILE NO.2 THROAT(RUN #4)

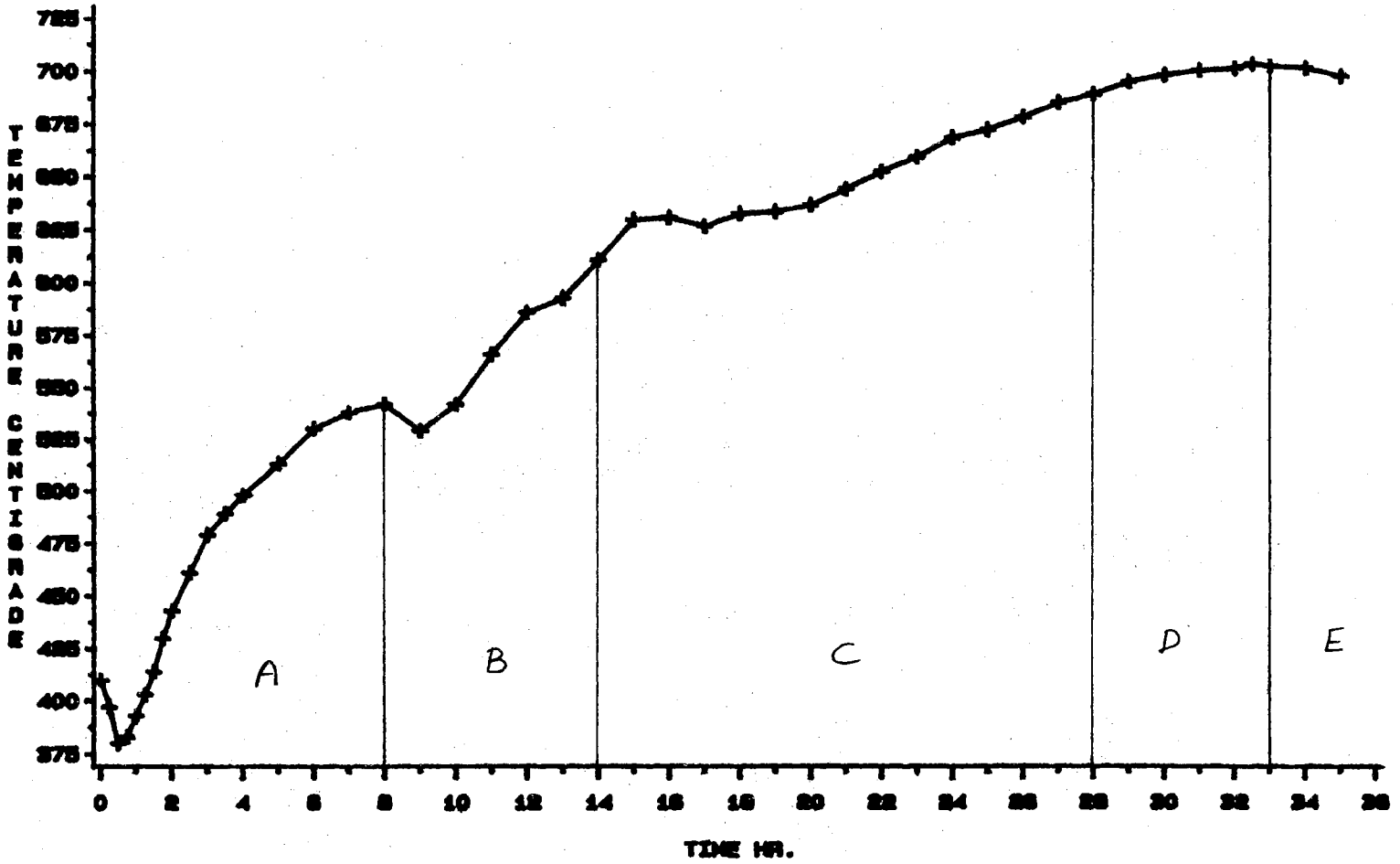

FIGURE 22. TEMPERATURE PROFILE NO.3 SECONDARY CHAMBER(RUN #4)

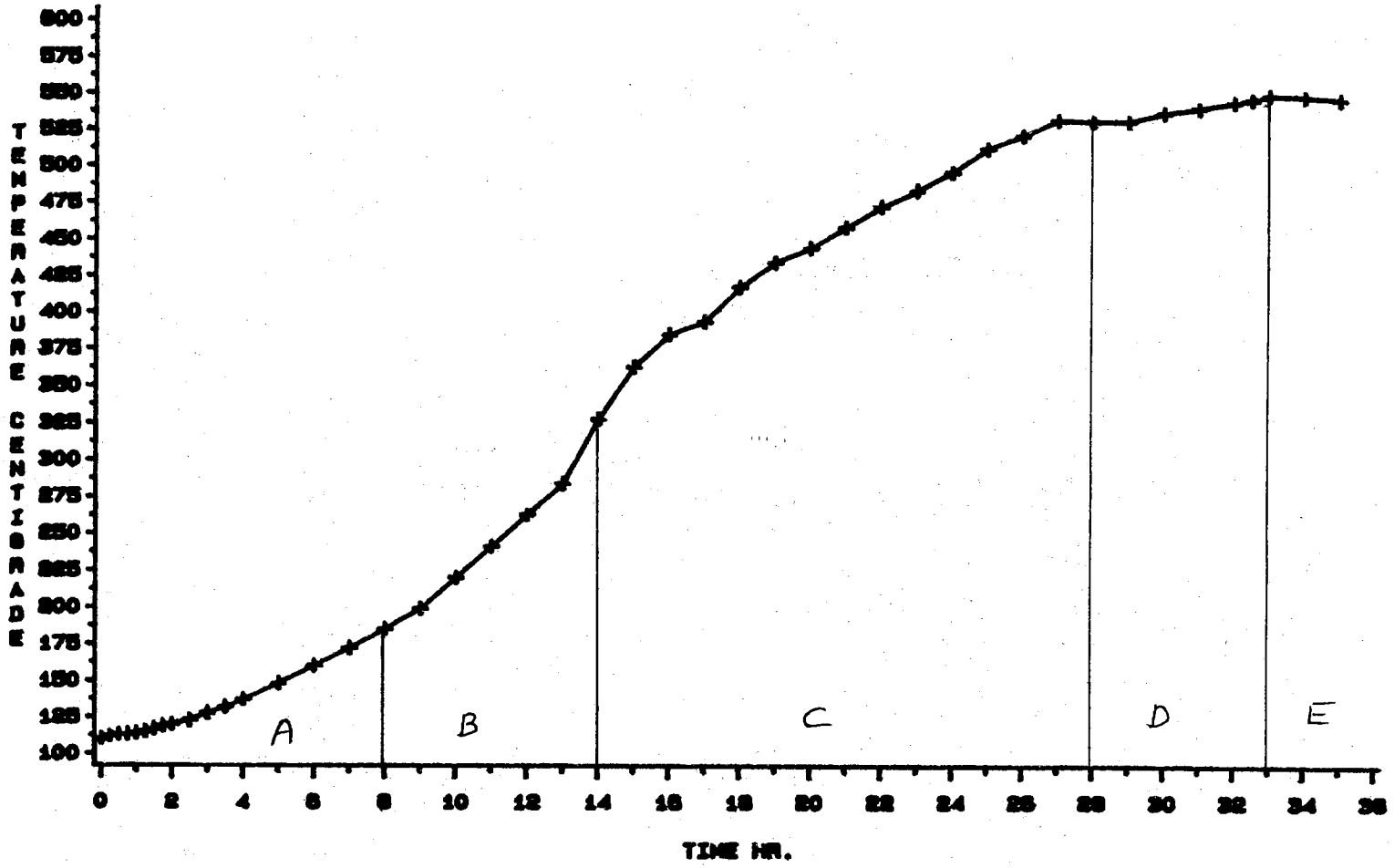

FIGURE 23. TEMPERATURE PROFILE NO.4 SECONDARY CHAMBER WALL(RUN #4)

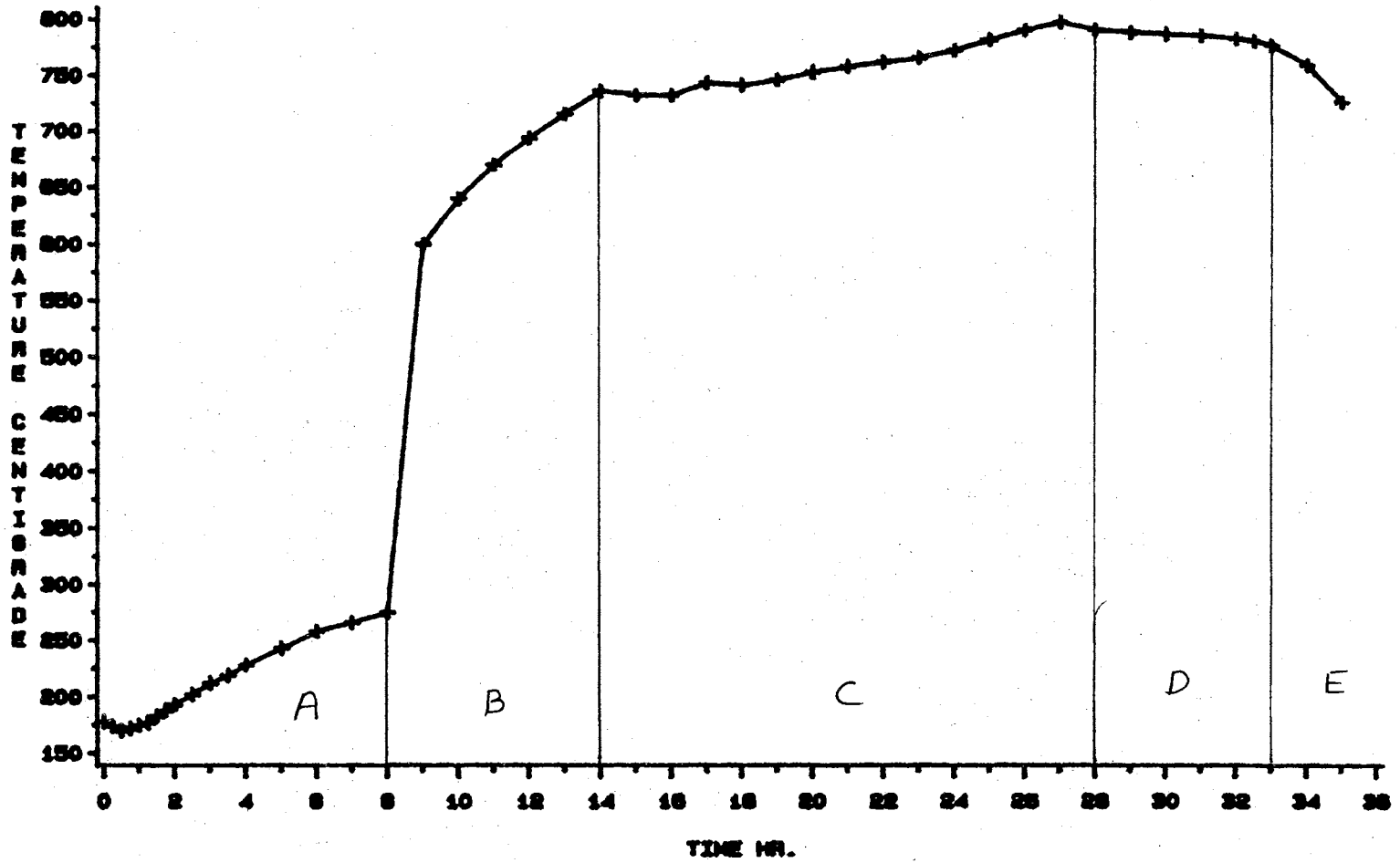

FIGURE 24. TEMPERATURE PROFILE NO.5 FLUE GAS(RUN #4)

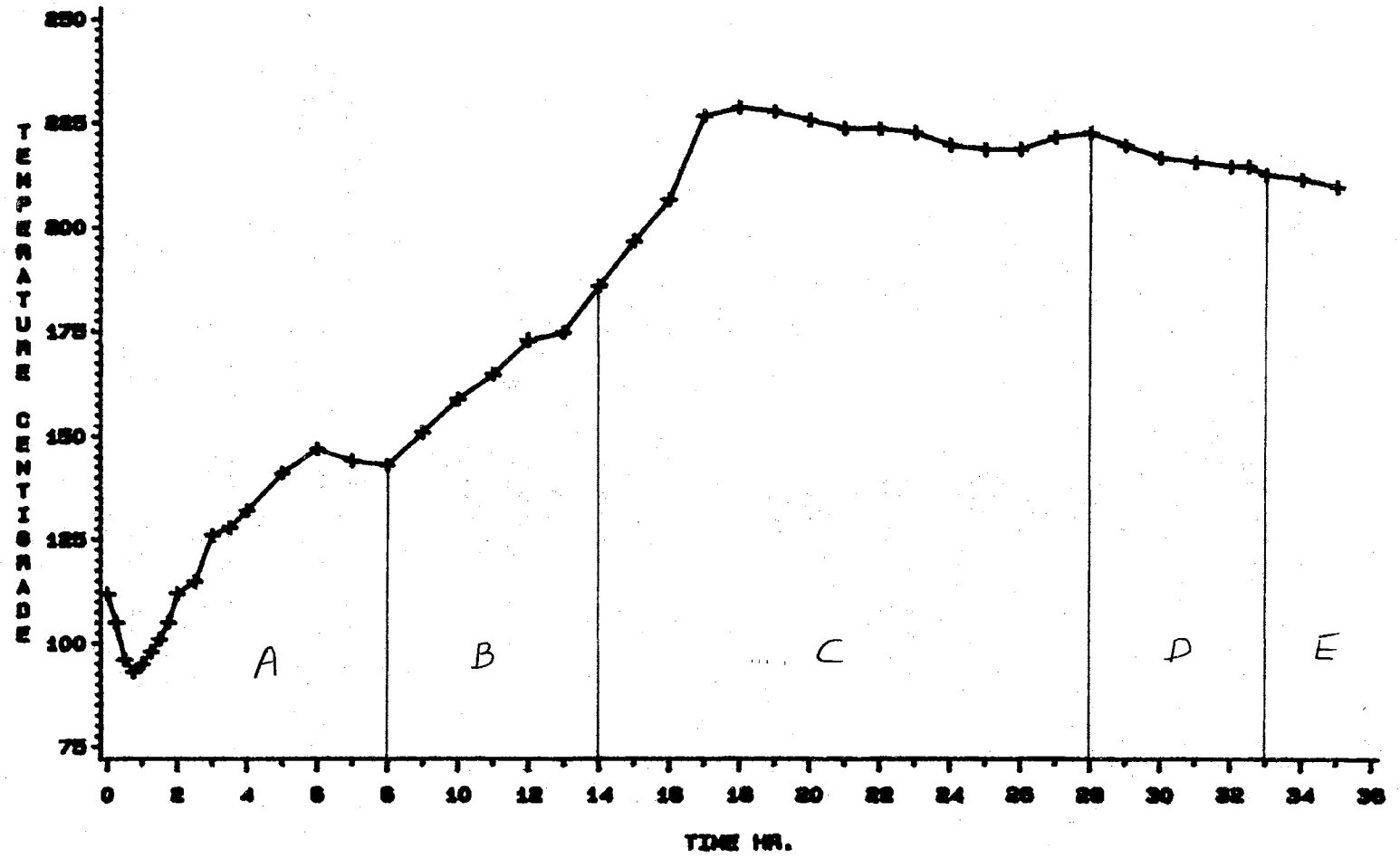

FIGURE 25. TEMPERATURE PROFILE NO.9 AIR HEAT EXCHAGER#1(RUN #4)

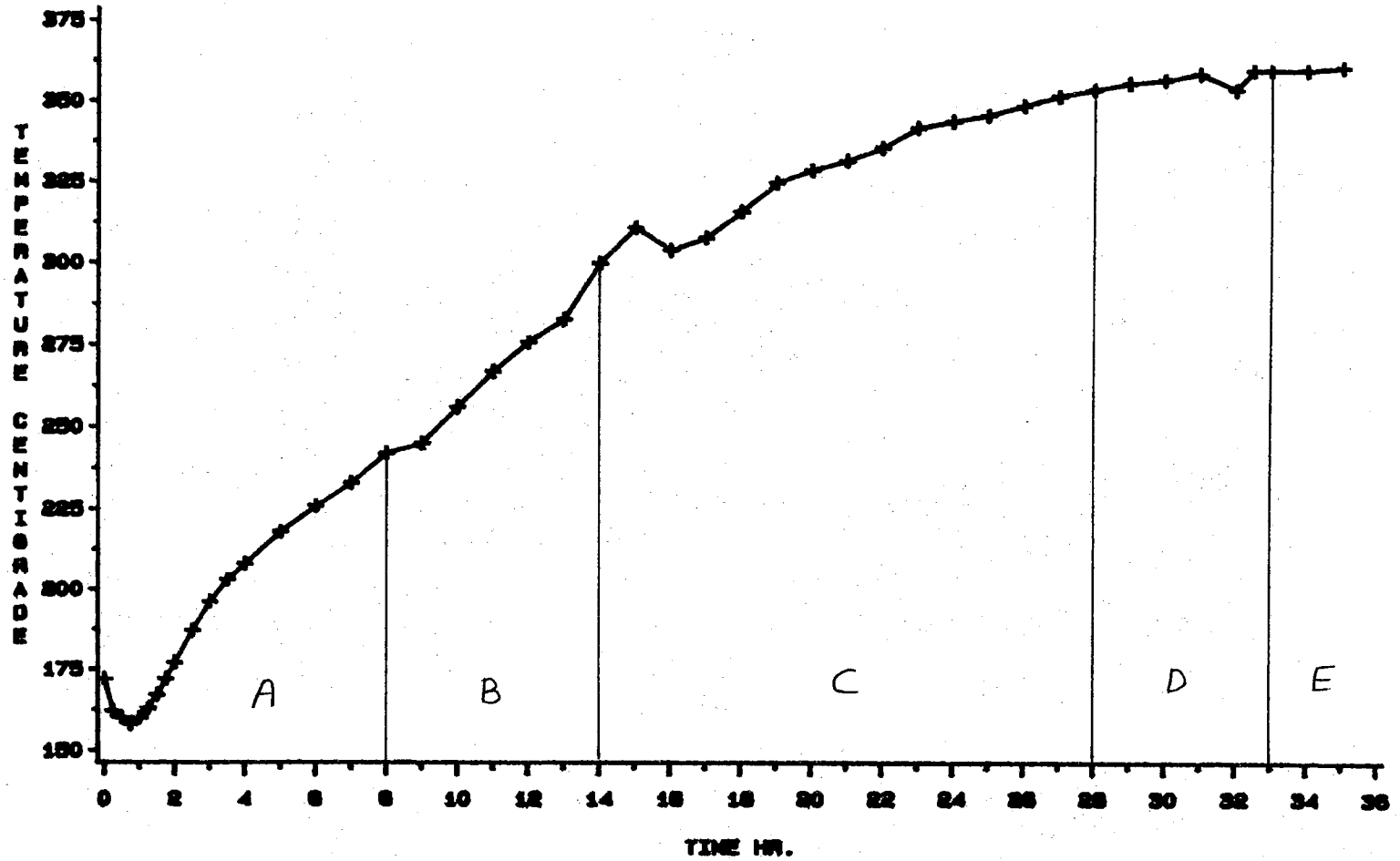

FIGURE 26. TEMPERATURE PROFILE NO.10 AIR HEAT EXCHANGER #2(RUN #4)

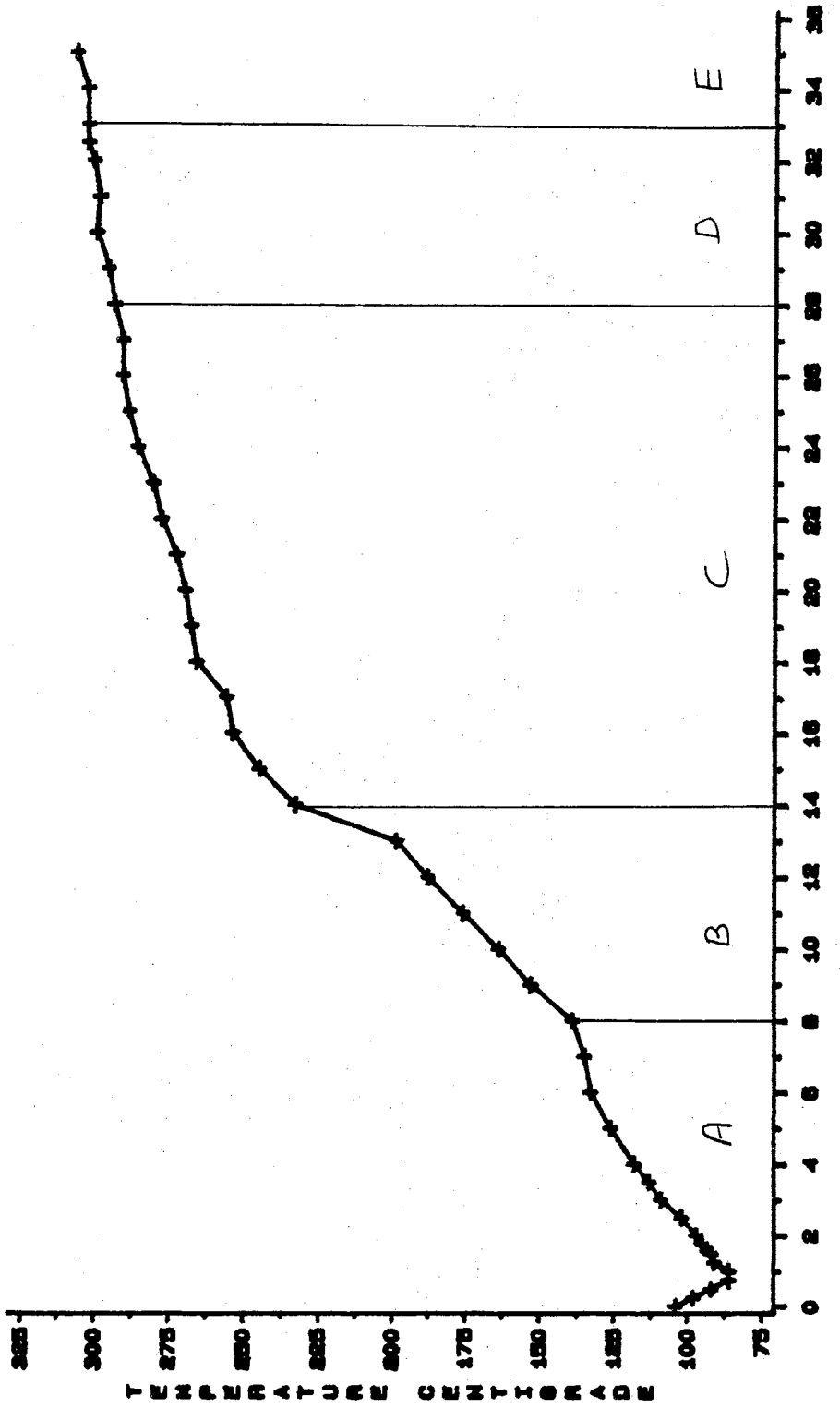

FIGURE 27. TEMPERATURE PROFILE NO.11 AIR HEAT EXCHANGER #3(RUN #4)

occurred in the first two heat exchangers. Temperature profiles are shown in Figures 25-27 for air exiting the heat exchangers.

Period B in these figures represent the period when the flue gas temperature increased suddenly. Similar to the second run, an increase in the flue gas temperature caused a momentary decrease in the temperatures of the primary chamber, the throat and the upper section of the secondary chamber. The temperature in the secondary chamber did not increase as fast in period B as it did in period A. As shown in Figure 24, the wall temperature showed the opposite effect. It increased relatively fast in this period compared period A.

The flue gas temperature jumped from 275°C to 600°C after the eight hours. Temperatures of air coming out of the top two heat exchangers did not show any effects due to the increase in the flue gas temperature. The temperature of the air exiting the third heat exchanger increased relatively fast in period B, implying that the flue gas temperature affected the lower portion of the secondary chamber.

After fourteen hours, which marks the start of period C, the secondary and the tertiary air preheat temperatures were lowered by 30°C to see the affects on furnace temperatures. It was observed that lowering the temperature of the combustion air by a few degrees did not

have any significant affects on the furnace temperatures. No other changes were introduced in this period. During this period all temperatures increased gradually except for the temperature of the air exiting the top heat exchanger. At the end of this period the system had achieved steady state conditions and at this time the temperature in the primary chamber was 1015°C.

Period D represents the time when the preheaters for the combustion air were turned off. Temperatures in the primary chamber, in the throat and in the secondary chamber decreased by a few degrees due to this change. Air exiting the top heat exchanger also showed a similar effect. Other temperatures were not affected by this change.

Period E represents the time when the damper controlling the induced draft fan was closed half way. As seen from these figures, the temperature dropped in all cases except for the wall temperature of the secondary chamber.

Figure 28 shows the flue gas composition during the run. Initially the flue gas contained a large amount of O_2 and a small amount of CO_2. With passing time as the temperature increased, oxygen content decreased and carbon dioxide content increased. After the 8th hour there was a huge increase in CO_2 content and a huge decrease in O_2 content. Slight changes in composition were observed when furnace conditions were changed as mentioned above.

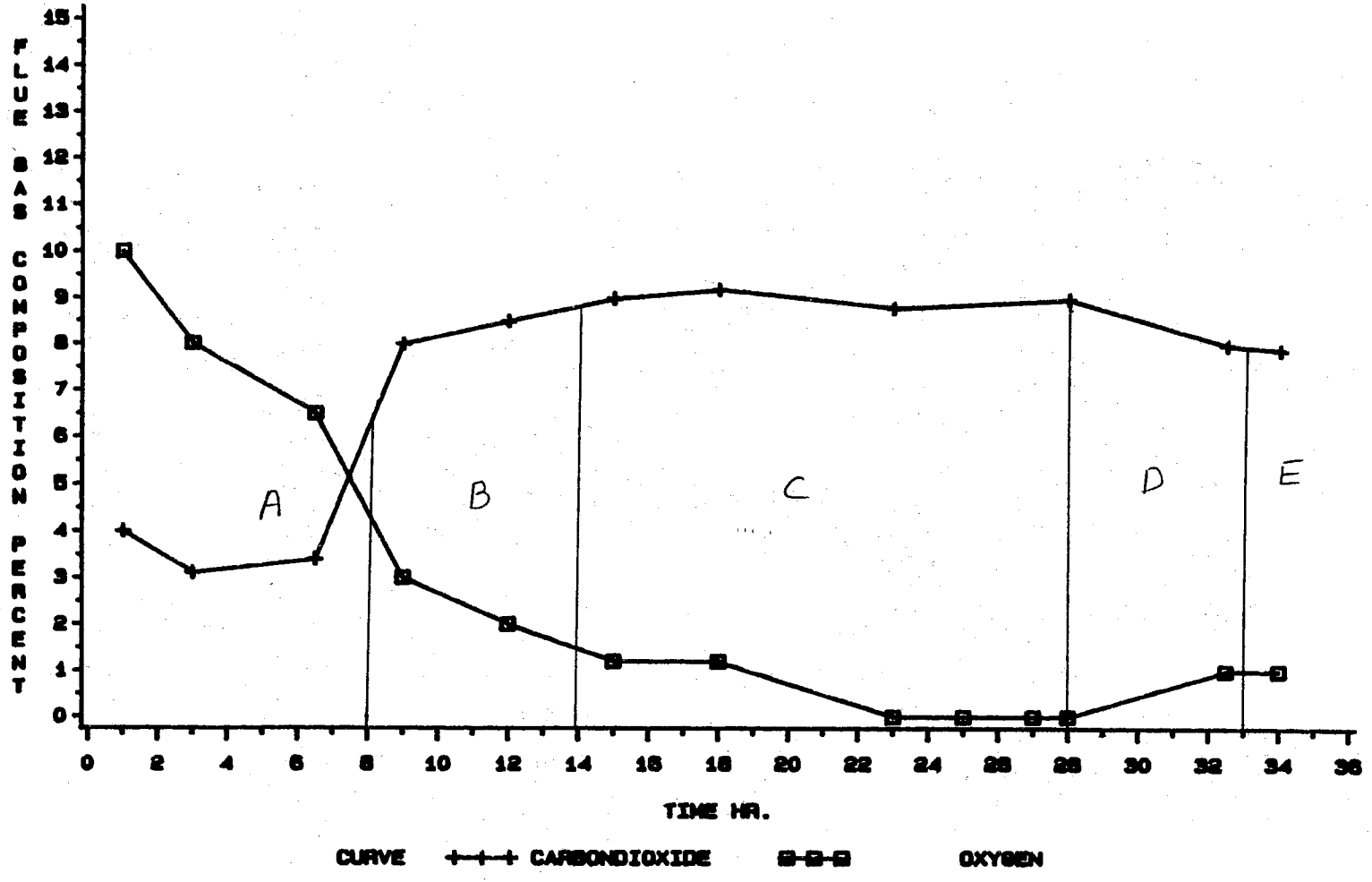

FIGURE 28. FLUE GAS COMPOSITION(RUN #4)

An increase in O_2 content and decrease in CO_2 content was observed during these operational changes.

Primarily the temperature of greatest concern was the temperature in the primary chamber. The maximum temperature attained in the primary chamber during this run was 1015°C. As anticipated earlier that the furnace would take a long time to achieve steady state, the furnace achieved steady state conditions around the 28th hour of operation. During this run after 27 hours of operation, when the temperature of the exit air from the second heat exchanger was 291°C, the hose carrying the hot air started smoking. The hose was pulled off and the hot air was allowed to escape into the room. After the furnace had cooled down, the front door of the furnace was opened to analyze if any damage has occurred inside the furnace. One of the bricks from the arch in the primary chamber had fallen off.

In this run the same phenomena of sudden increase in the temperature of the flue gas was observed. A fact that was established in this run was that to attain an optimum combustion situation in the furnace, the damper should be fully opened.

Run No.5 using Natural Gas and Coal

In this run, the furnace was first heated up with natural gas and then tested with coal. Before starting this run, the equipment that were damaged during prior runs were repaired. The brick that came off from the arch in the primary chamber was mortared back. Originally, the water sampling port was designed in such a way that there were two stainless steel U tubes welded to a joint which connected these tubes to the water hoses. One of the U tube was removed so that a swage lock connection could be used instead welding. Since the furnace was opened after the last run, different temperature profiles were expected in this run.

Temperature profiles are shown in Figures 29-37. In the beginning stages of this run, temperature profiles were similar to the previous runs. However, this time there was no sudden increase in the flue gas temperature as seen in the previous runs. Period A in these figures represents the period before the coal feed was turned on. Some fluctuation can be seen in Figure 34 for the water outlet temperature between the 12th and the 14th hour. This was due to an adjustment in the water flow rate.

At the end of the 28th hour when the temperature in the primary chamber was 956°C, coal feed was turned on. Period B in these figures represent the time period when

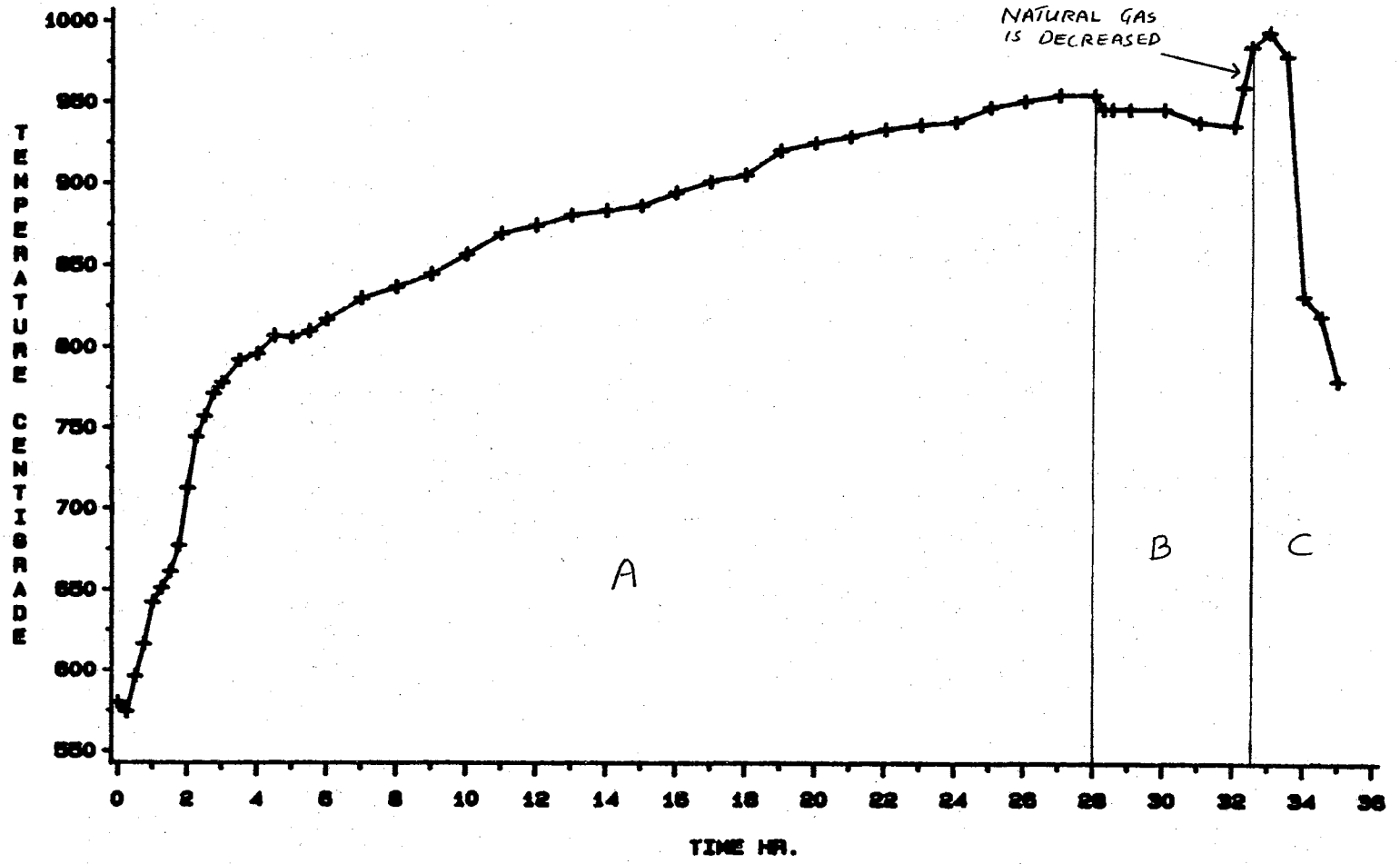

FIGURE 29. TEMPERATURE PROFILE NO.1 PRIMARY CHAMBER(RUN #5)

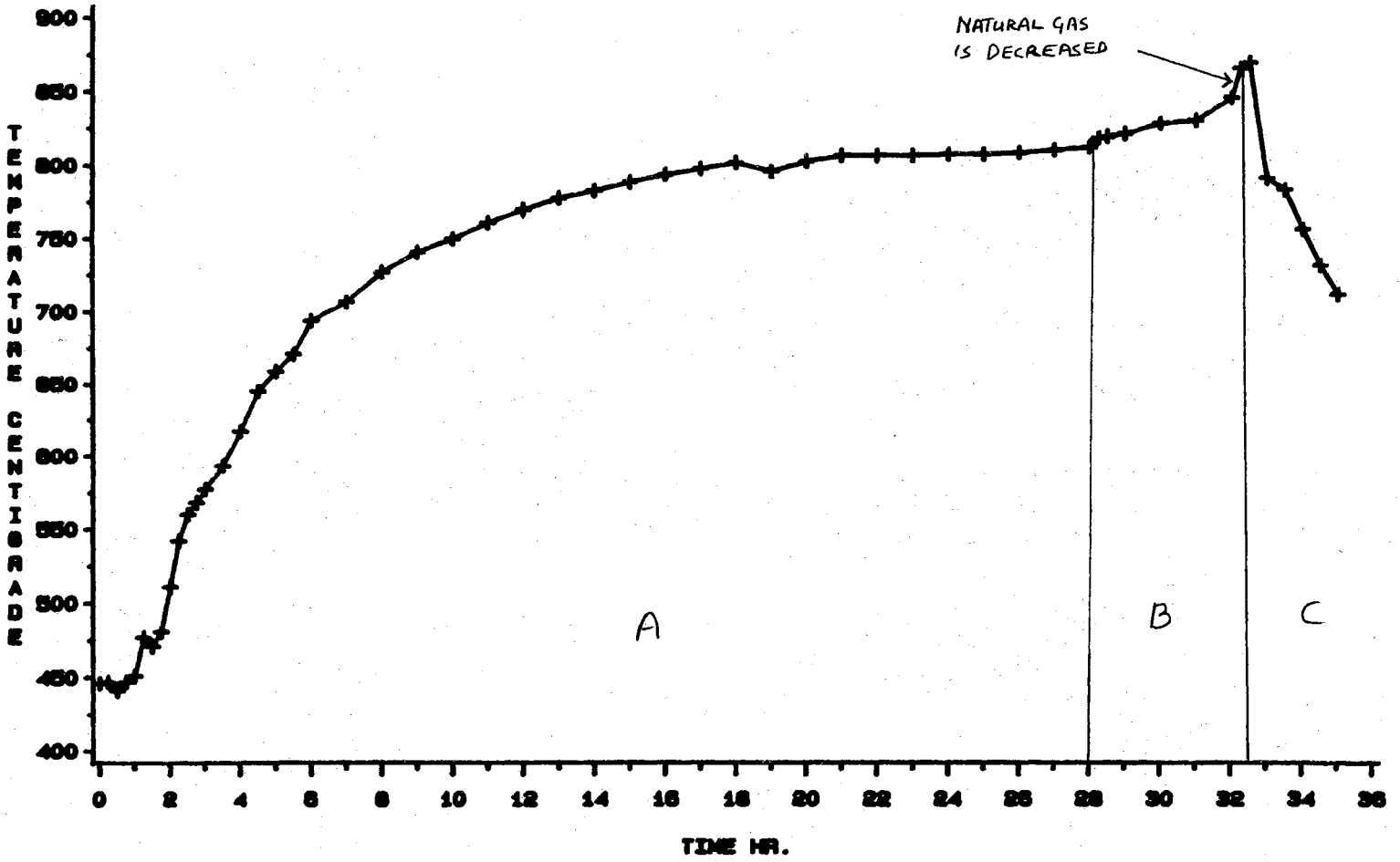

FIGURE 30. TEMPERATURE PROFILE NO.2 THROAT(RUN #5)

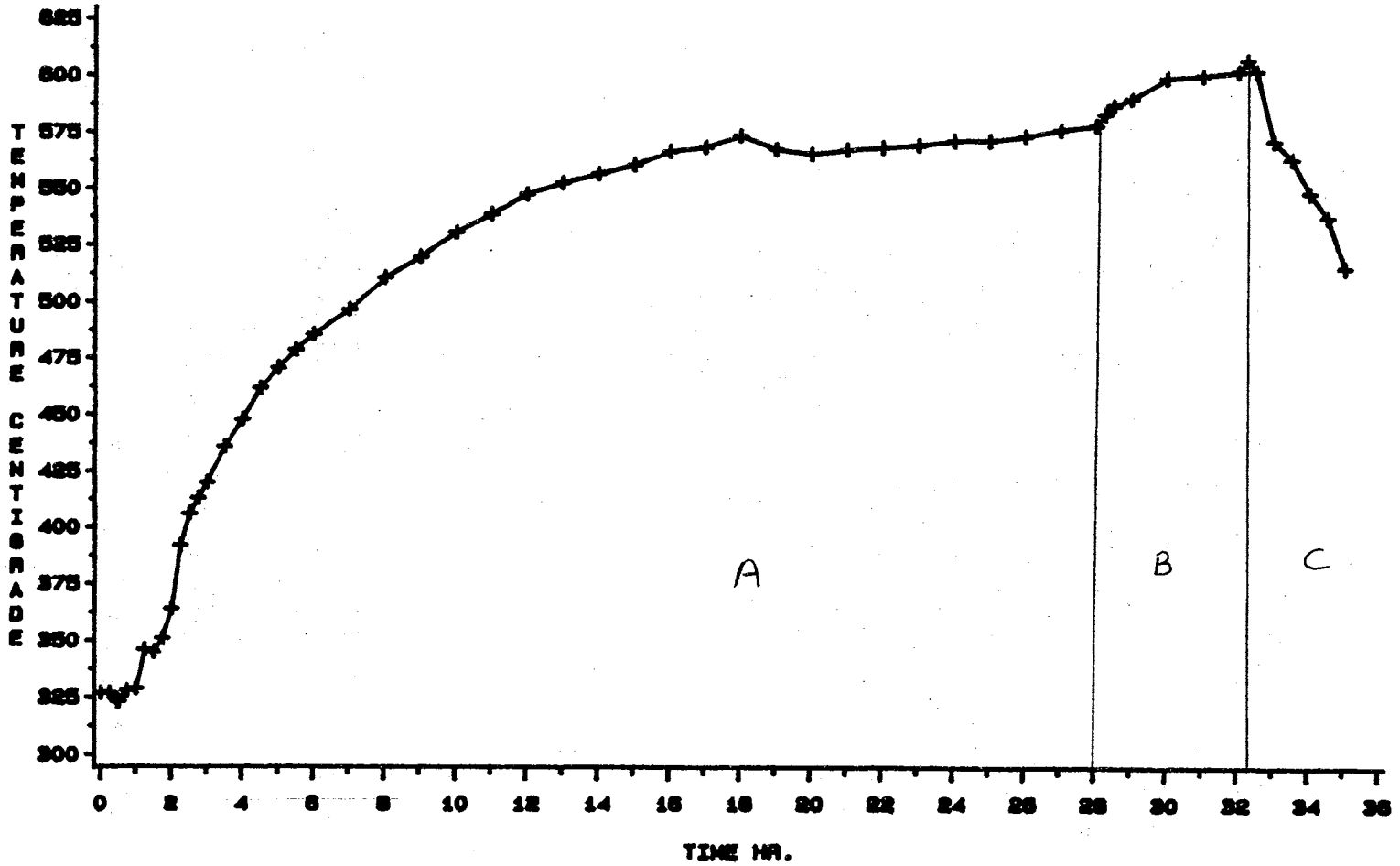

FIGURE 31. TEMPERATURE PROFILE NO.3 SECONDARY CHAMBER(RUN #5)

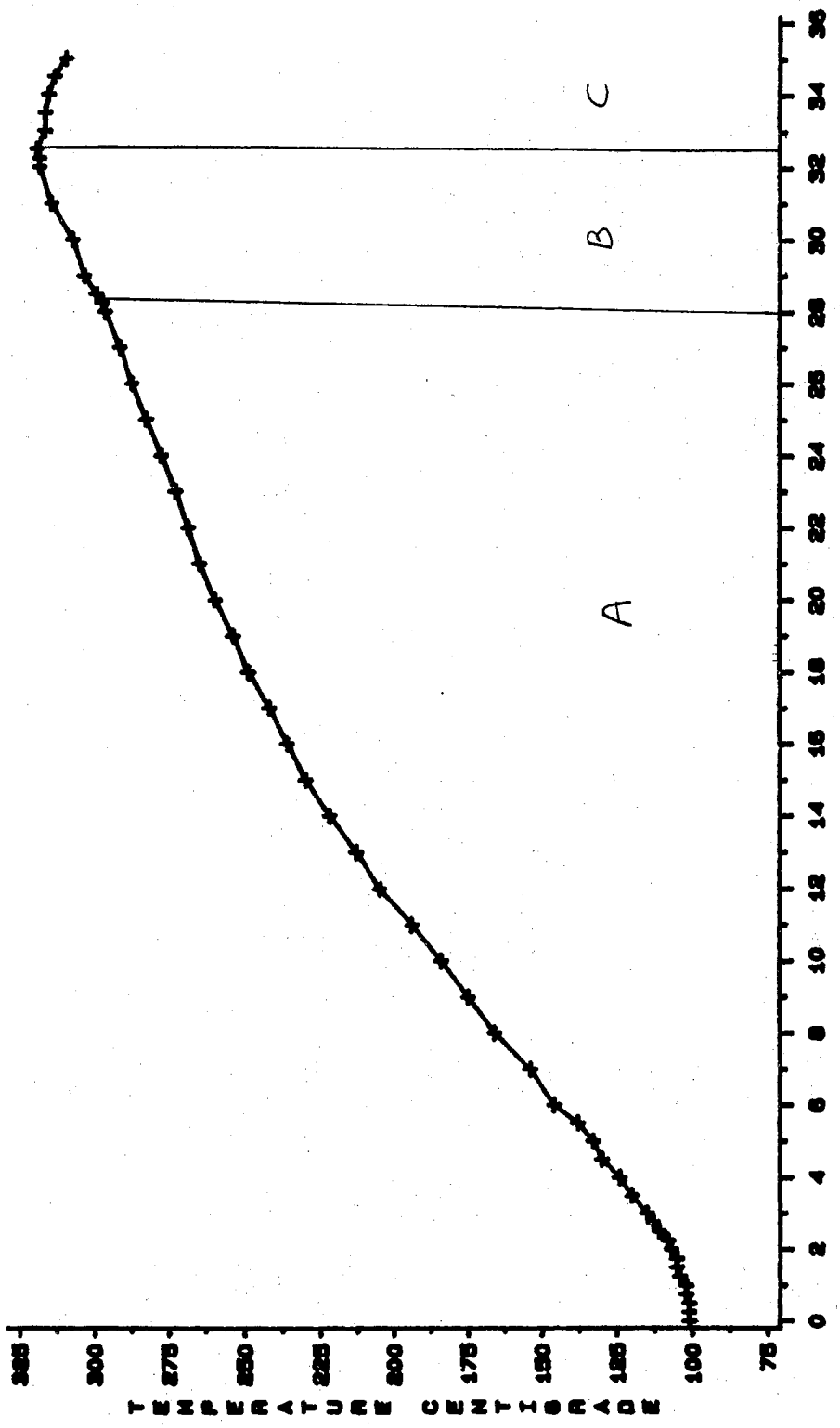

FIGURE 32. TEMPERATURE PROFILE NO.4 SECONDARY CHAMBER WALL(RUN #5)

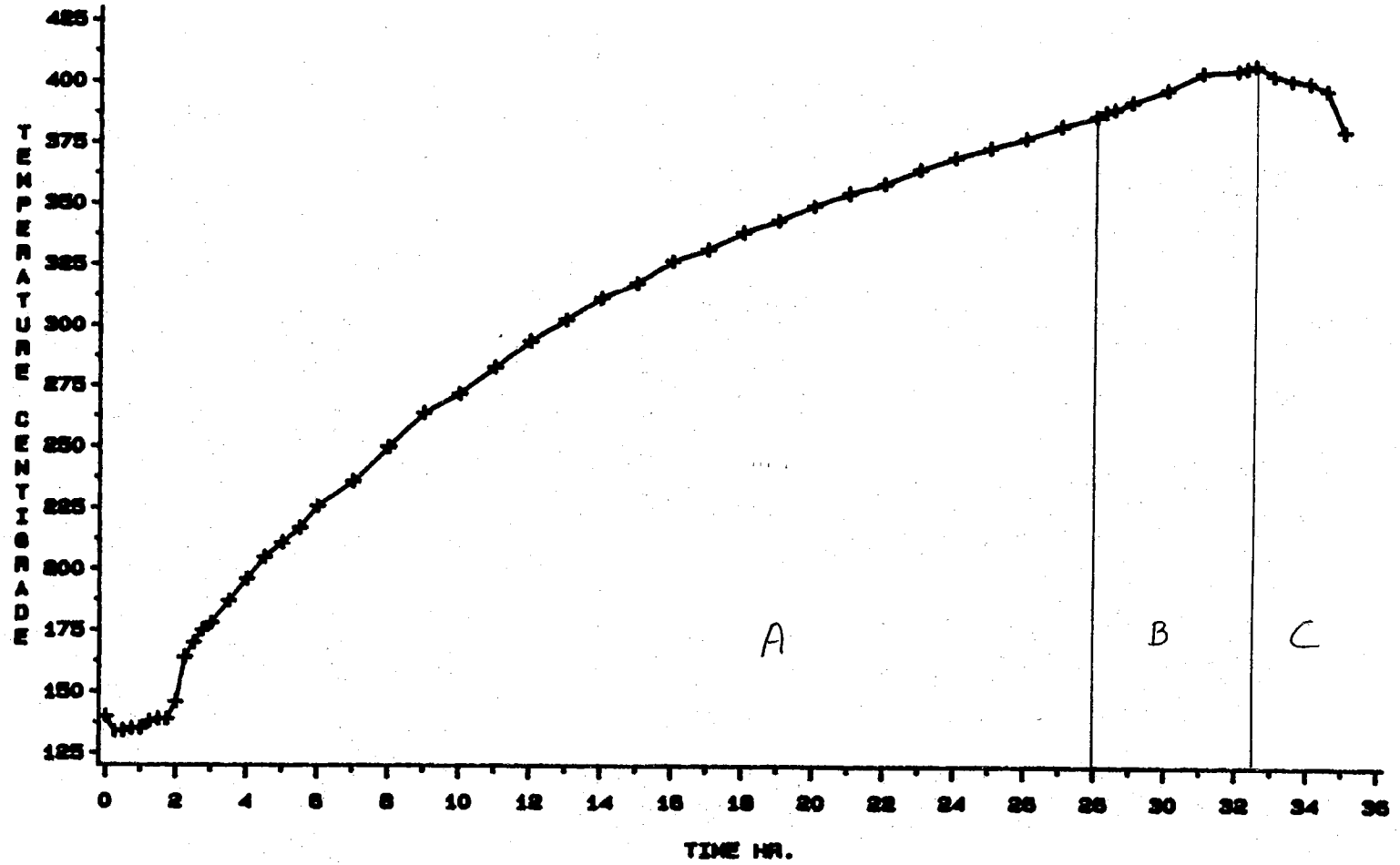

FIGURE 33. TEMPERATURE PROFILE NO.5 FLUE GAS(RUN #5)

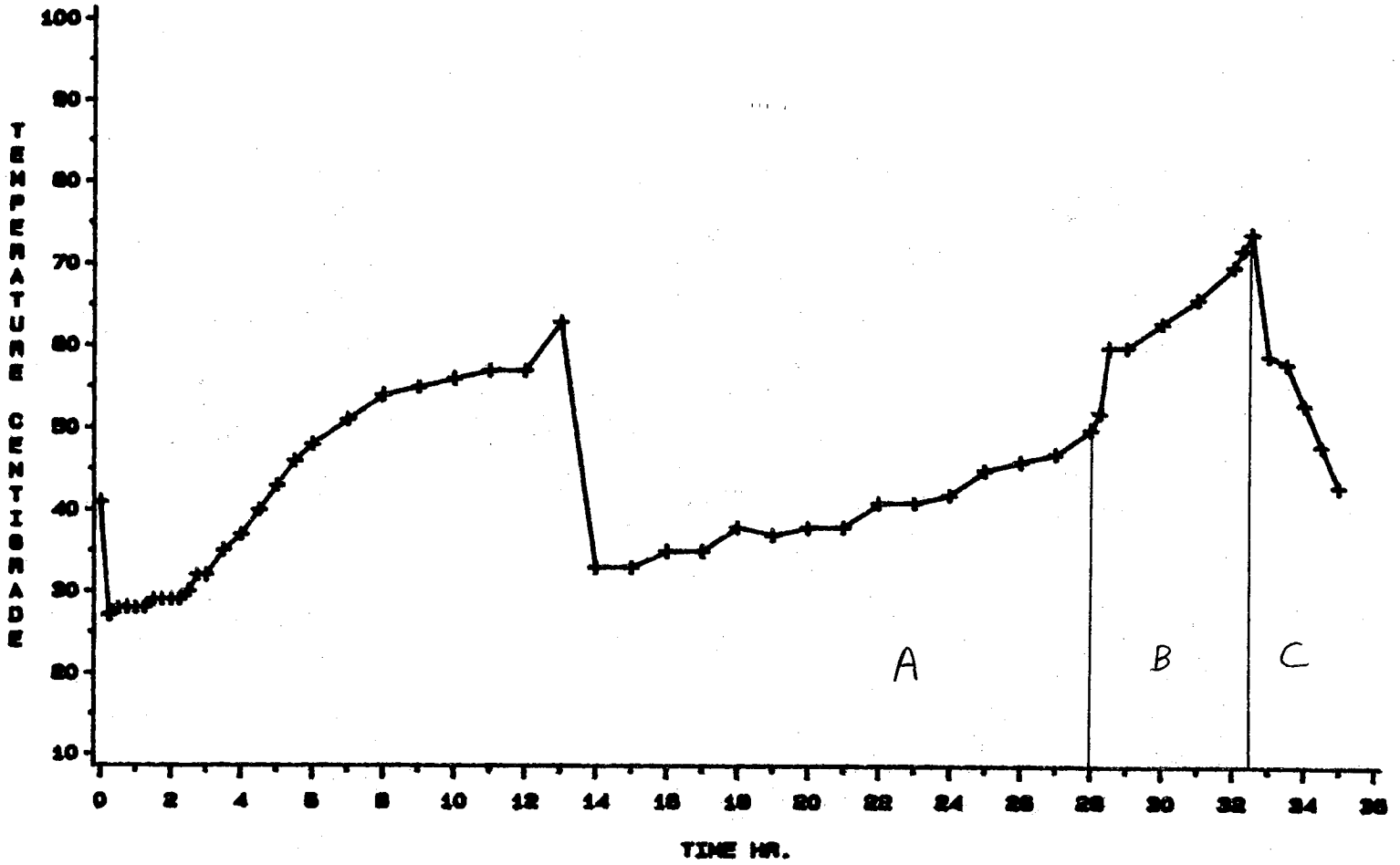

FIGURE 34. TEMPERATURE PROFILE NO.8 SAMPLING PORT WATER(RUN #5)

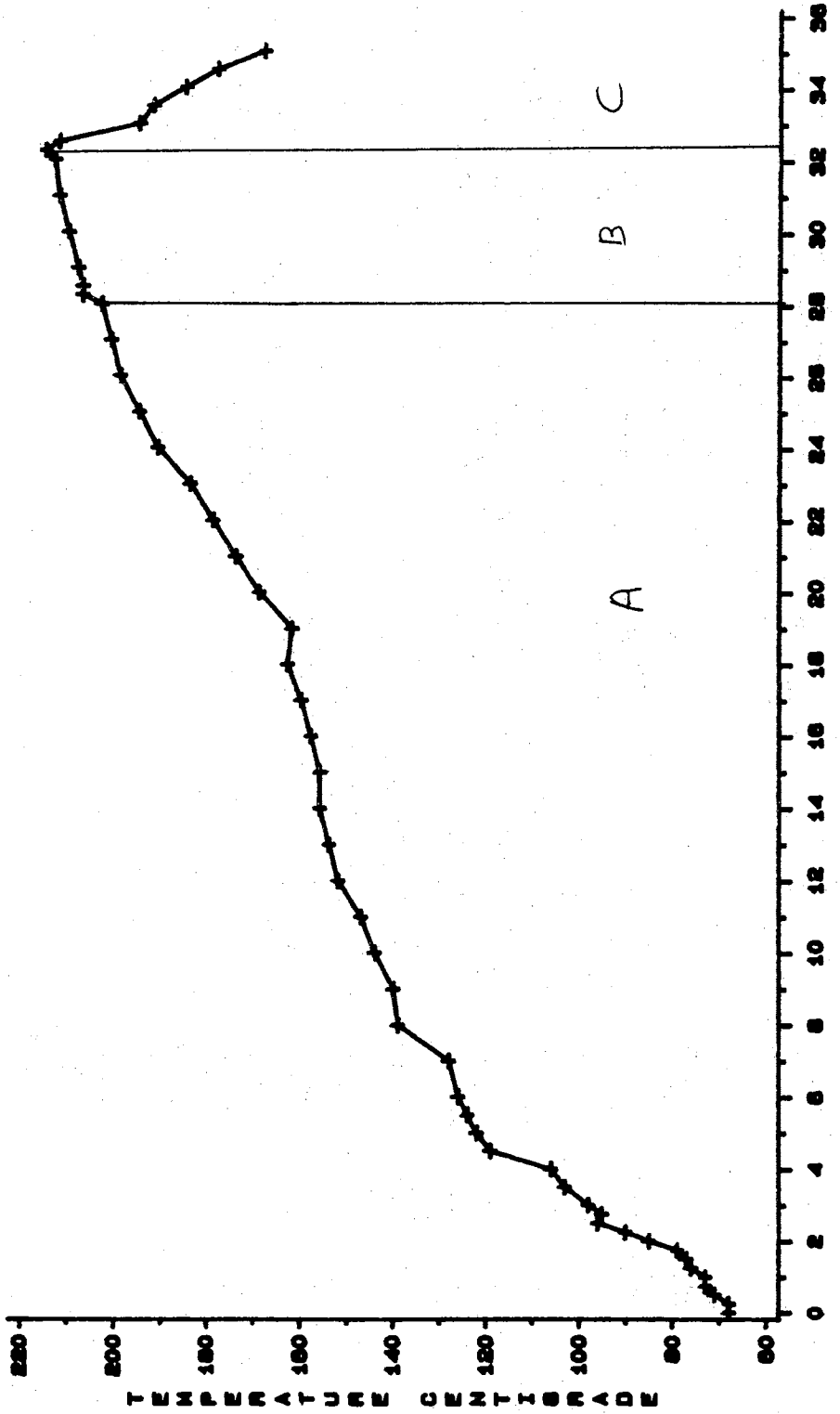

FIGURE 35. TEMPERATURE PROFILE NO.9 AIR HEAT EXCHANGER #1 (RUN #5)

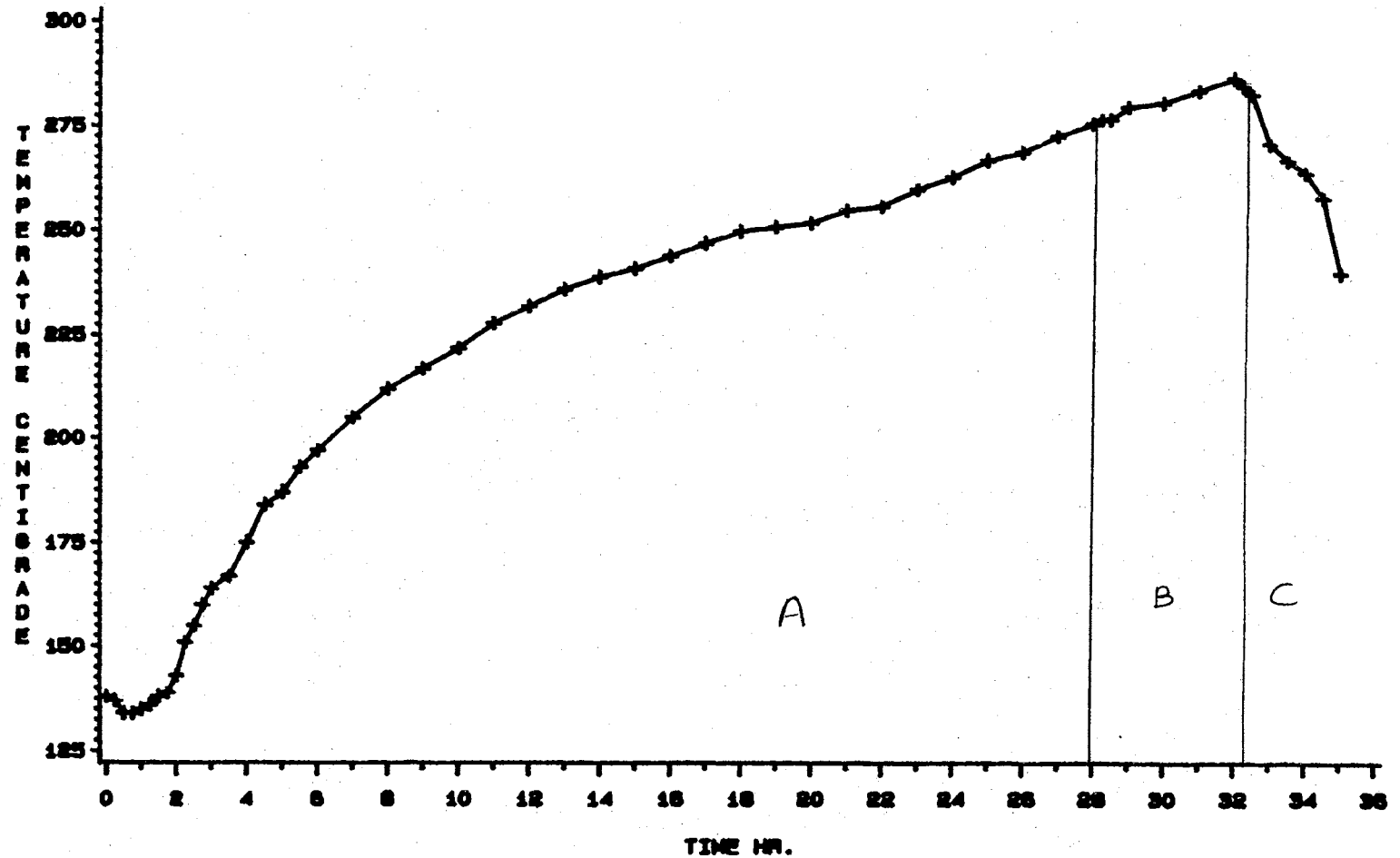

FIGURE 38. TEMPERATURE PROFILE NO.10 AIR HEAT EXCHANGER #2(RUN #5)

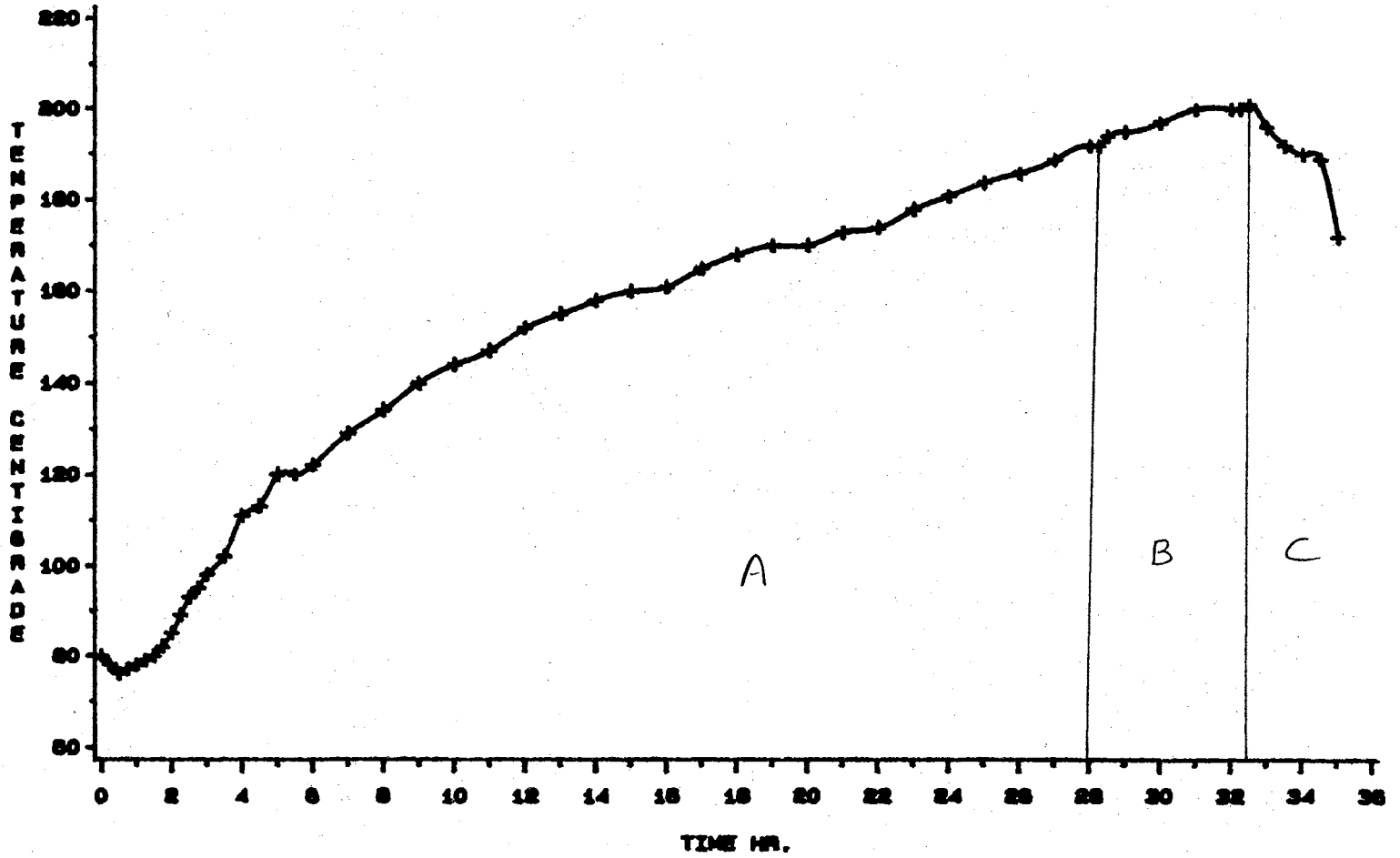

FIGURE 37. TEMPERATURE PROFILE NO.11 AIR HEAT EXCHANGER #3(RUN #5)

natural gas and coal were used as fuel. This period lasted for 4.5 hours. When the coal feed was turned on, the primary chamber showed a slight drop in temperature. Temperature in the throat and in the secondary chamber showed a slight increase. The wall temperature of the lower secondary chamber and the flue gas temperature remained unaffected during this period as shown in Figures 32 and Figure 33. There was an increase in water outlet temperature, this can be attributed to the change in the flow rate of water or the fact that there was better heat transfer at that moment since there was a temperature drop observed in the primary chamber. Air coming out of the heat exchangers in the secondary chamber showed no drastic change in temperature, since steady state conditions did not yet exist, as shown in Figures 35-37. One important thing worth mentioning here is that at times the flow rate of coal did not seem to be continuous and it seemed that at certain times, the coal flow rate had stopped. There was no way of making sure since the natural gas kept the temperature in the furnace high.

After 32.5 hours, the natural gas was completely turned off and from there on the furnace was operated only by coal. This period is represented in these figures by Period C. This period lasted for only two hours because as thought earlier, the flow rate of coal was hindered at different times. It can be seen from Figure 29 and Figure

30 for a short while there was a very sharp increase in temperatures in the primary chamber and in the throat, when the natural gas was being gradually turned off just before the start of Period C. Then there was a huge decrease in temperatures especially in the primary chamber in Period C. In the secondary chamber, the temperature decreased as soon as the natural gas was turned off indicating combustion in the secondary chamber. The wall temperature also showed a little decrease as did the flue gas temperature. Outlet water and air temperatures also decreased with time. The decrease in these temperatures slowed down with time. During this period coal flow rate was varying all the time. The reason being that the coal particles were not uniform in size and some particles were too big for the tube in which the coal was carried in by the primary air. One very important thing observed was at one point the coal feed completely stopped for about 10 minutes. During this time the temperature in the primary chamber dropped from 820°C to 760°C. The coal feed was restarted at this point. The ignition of coal also restarted implying that the wall temperature was high enough for ignition to take place even though there was no natural gas in the furnace.

Flue gas composition was measured using Orsat meters. Flue gas composition is shown in Figure 38. As seen from this figure, with the passage of time oxygen decreased and carbon dioxide increased and this pattern continued until

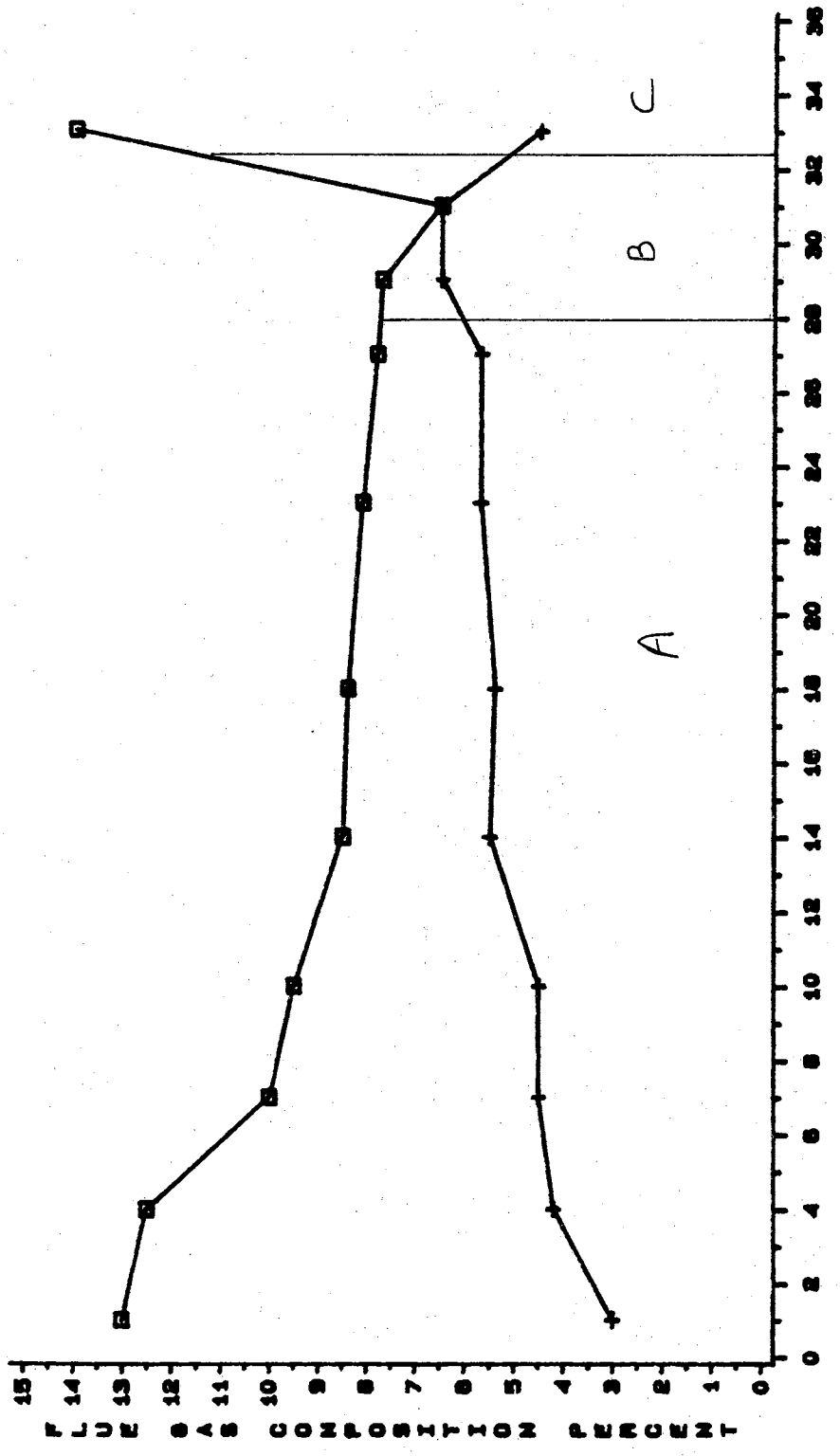

FIGURE 38. FLUE GAS COMPOSITION(RUN #5)

the natural gas was fully turned off. This is understood because once there was no natural gas in the furnace, more excess oxygen was left and less carbon dioxide was formed.

This run lasted for 34.5 hours. After the furnace had cooled, the front door of the furnace was removed for inspection. This time the furnace did not sustain any damage. Coal ash was found at the bottom of the primary chamber. There were no slag deposits on the water sampling port. The ash on the floor of the primary chamber was brown in color as shown in Figure 39. The front view of the entire furnace from inside is shown in Figure 40. The blackish portion on the outer surface of the furnace was due to the carbonization. There were deposits found on all three heat exchangers as seen in Figures 40-43. The deposit on the top heat exchanger was black in color and formed a flake type layer. The second heat exchanger had ash like dust attached on it and black flake on the front tips of the tubes as seen in Figure 42. In the third heat exchanger, there was a black layer of carbon all over it as seen in Figure 43. Careful examination of this figure would show the difference in the original tube color and the thick layer that was formed at the beginning of the heat exchanger tubes. From this run, the most important finding was that the furnace could be operated using coal, provided the furnace was heated to a very high temperature. This time there was no damaged done to the inside or the

FIGURE 39. RESIDUAL ASH ON THE FLOOR OF THE PRIMARY CHAMBER

FIGURE 40. INSIDE VIEW OF THE FURNACE

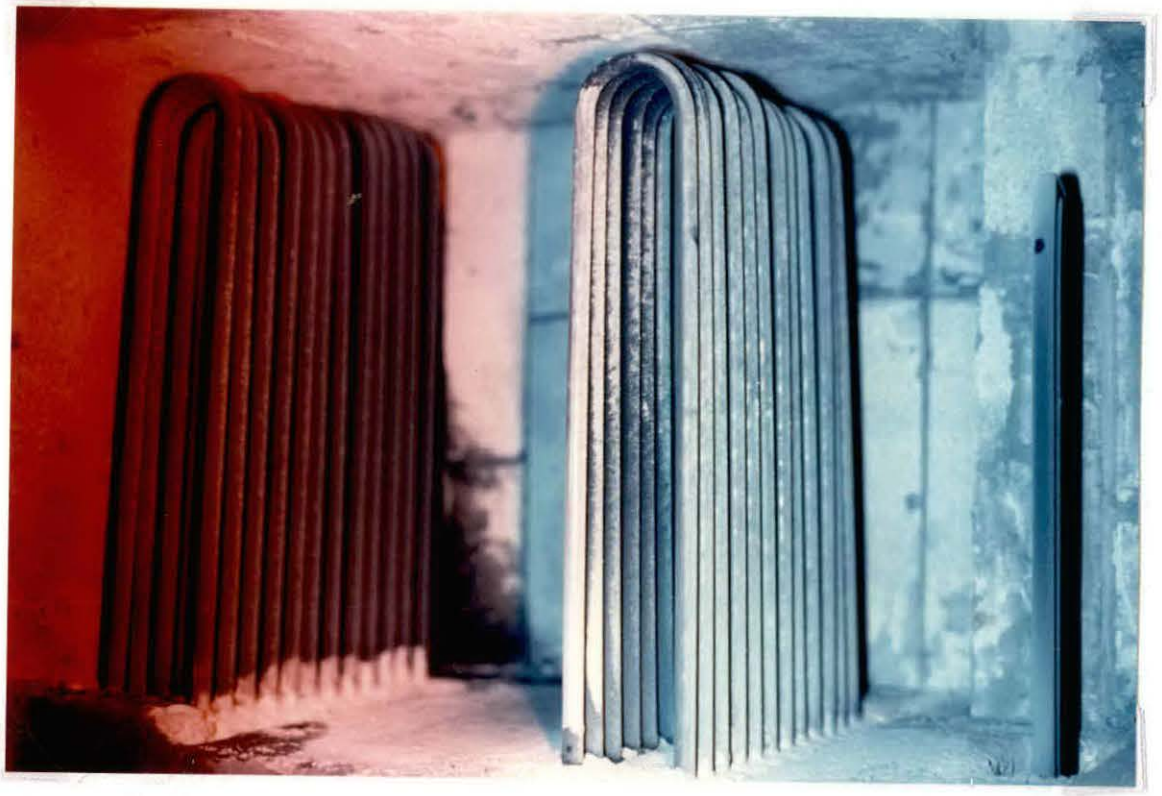

FIGURE 41. SECONDARY CHAMBER

FIGURE 42. SECOND HEAT EXCHANGER(SECONDARY CHAMBER)

FIGURE 43. THIRD HEAT EXCHANGER(SECONDARY CHAMBER)

outside of the furnace. Since the furnace had been opened prior to this run, the combustion situation was different and there was no sudden increase in the flue gas temperature. This run was stopped due to an obstruction in the coal feed.

Run No.6 using Natural Gas and Coal

This was the final run. It had already been proven that the furnace could be operated using coal, provided the furnace was preheated to a very high temperature. The main concern in this run was to check if the furnace could be operated for longer periods using coal. Before this run, coal was ground to 20 mesh using a small grinder. It took about two days to complete this process because of the limited facilities available for grinding coal. The furnace was first heated with natural gas and then coal was used. Since the furnace was opened after the last run, slightly different temperature profiles were expected for this run. The flow rate of the natural gas, the combustion air, the cooling air were kept the same as in the last run.

The temperature profiles for run number 6 are shown in Figure 44-52. Period A represents the first sixteen hours of the run. All the temperature profiles had similar patterns to previous runs. At the 16th hour the preheater for the secondary air broke. It was repaired by the 20th hour. Period B in these figures represents this time. In

this period temperatures at different locations in the furnace showed exactly the same patterns as seen in run no.4 when the preheaters were turned off. A decrease in temperatures in the primary chamber, in the throat and in the upper secondary chamber was observed. Other temperatures were not affected by this change.

In this run, a sudden increase in the flue gas temperature was observed after 27 hours. Period C represents the time before this happened. All the temperatures increased gradually during this period. Period D shows the temperature profiles when there was an increase in the flue gas temperature. As observed before in run no.4 there was a decrease in temperatures in the primary chamber, in the throat and in the secondary chamber and other temperatures were not effected by this change.

Period E represents the time when the coal feed was turned on and the natural gas was turned off. The coal feed was turned on when the temperature in the primary chamber was 927°C. In this run coal flow was held constant at 3.0 lbs per hr. The temperatures behavior in the furnace was similar to the last run. As soon as the natural gas was turned off, temperatures in the primary chamber, in the throat increased about 30°C and then they decreased very rapidly for about 10 minutes. In the primary chamber the temperature dropped from 962°C to 873°C. After this rapid drop, the temperature in the

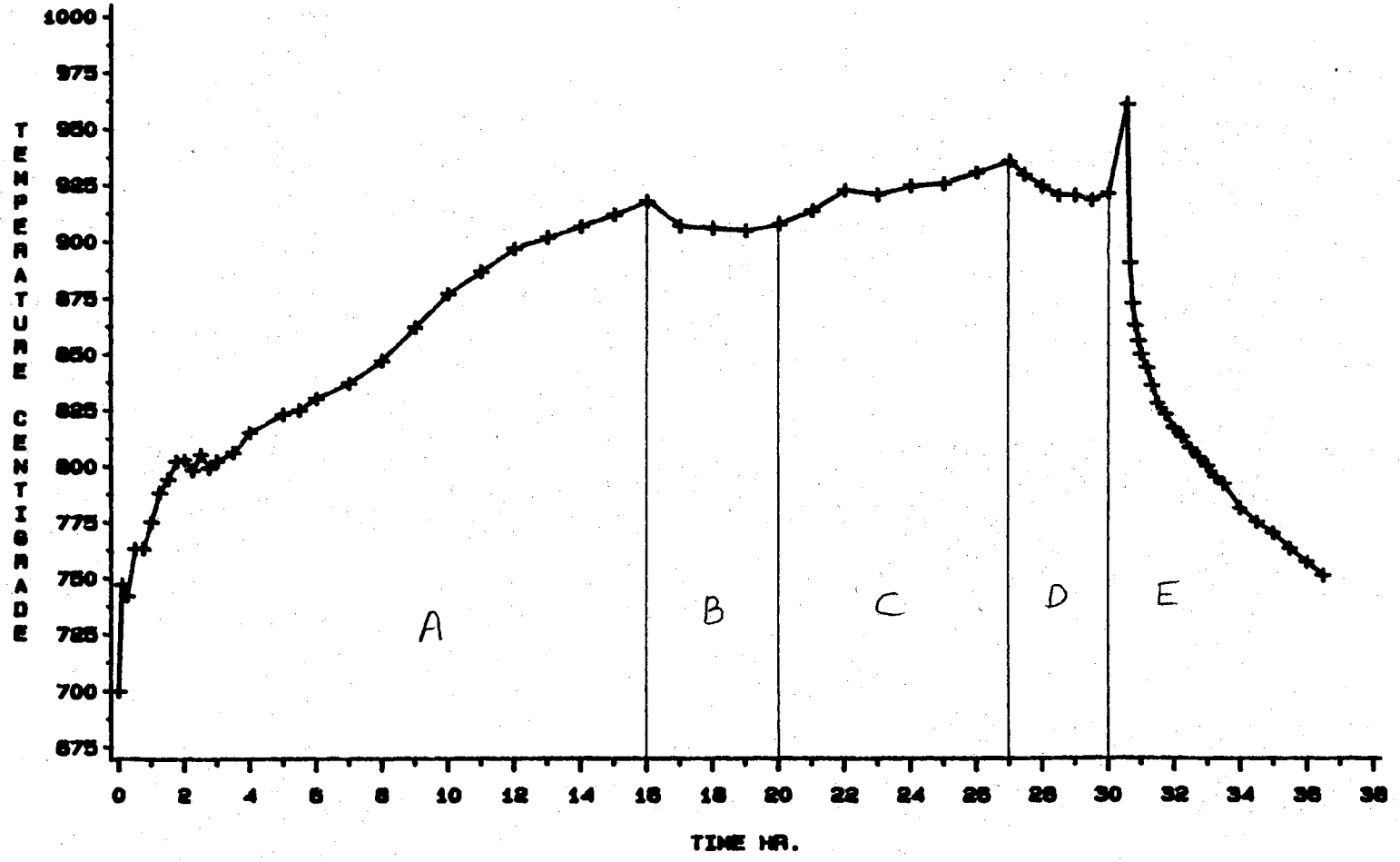

FIGURE 44. TEMPERATURE PROFILE NO.1 PRIMARY CHAMBER(RUN #6)

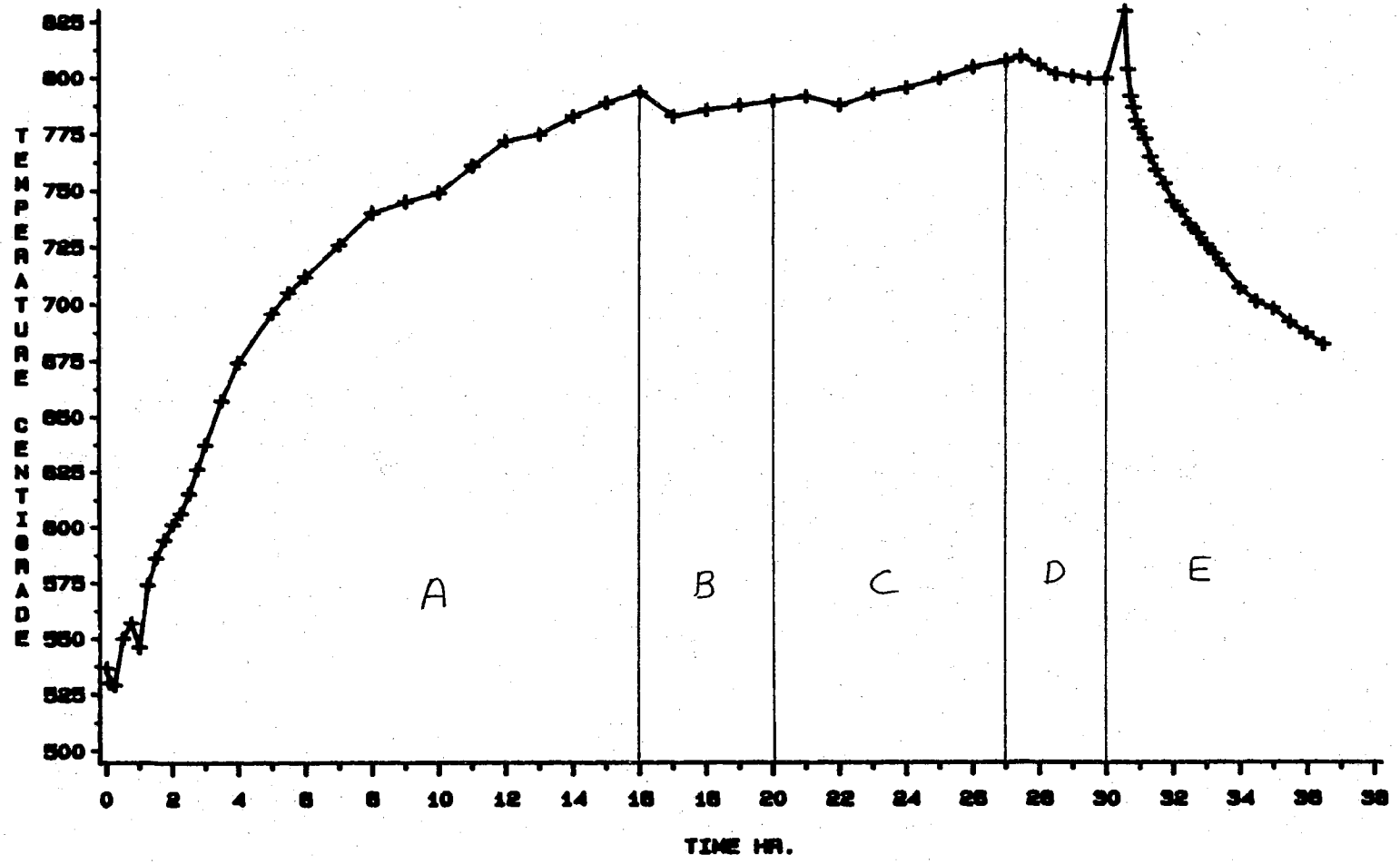

FIGURE 45. TEMPERATURE PROFILE NO.2 THROAT (RUN #6)

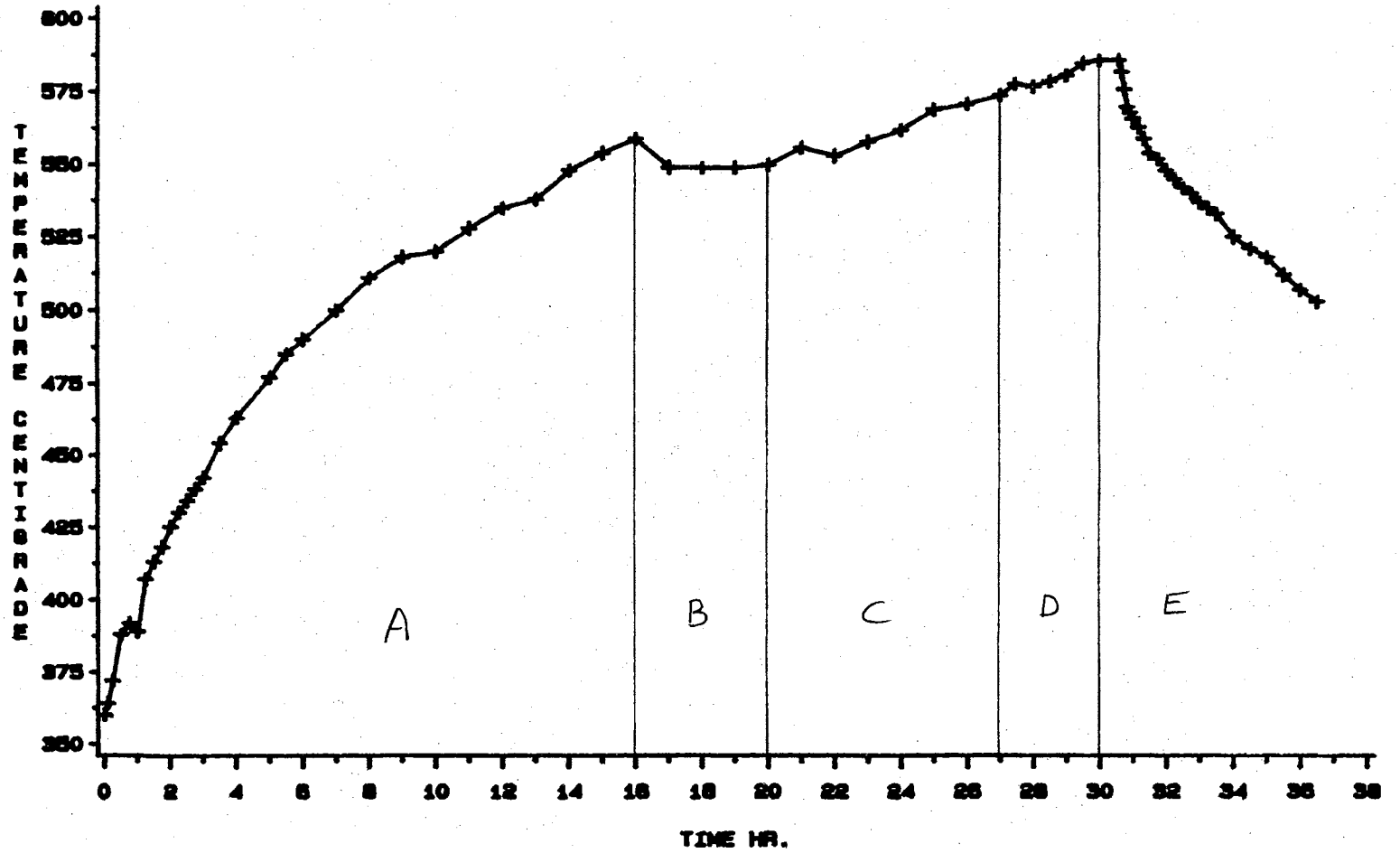

FIGURE 46. TEMPERATURE PROFILE NO.3 SECONDARY CHAMBER(RUN #6)

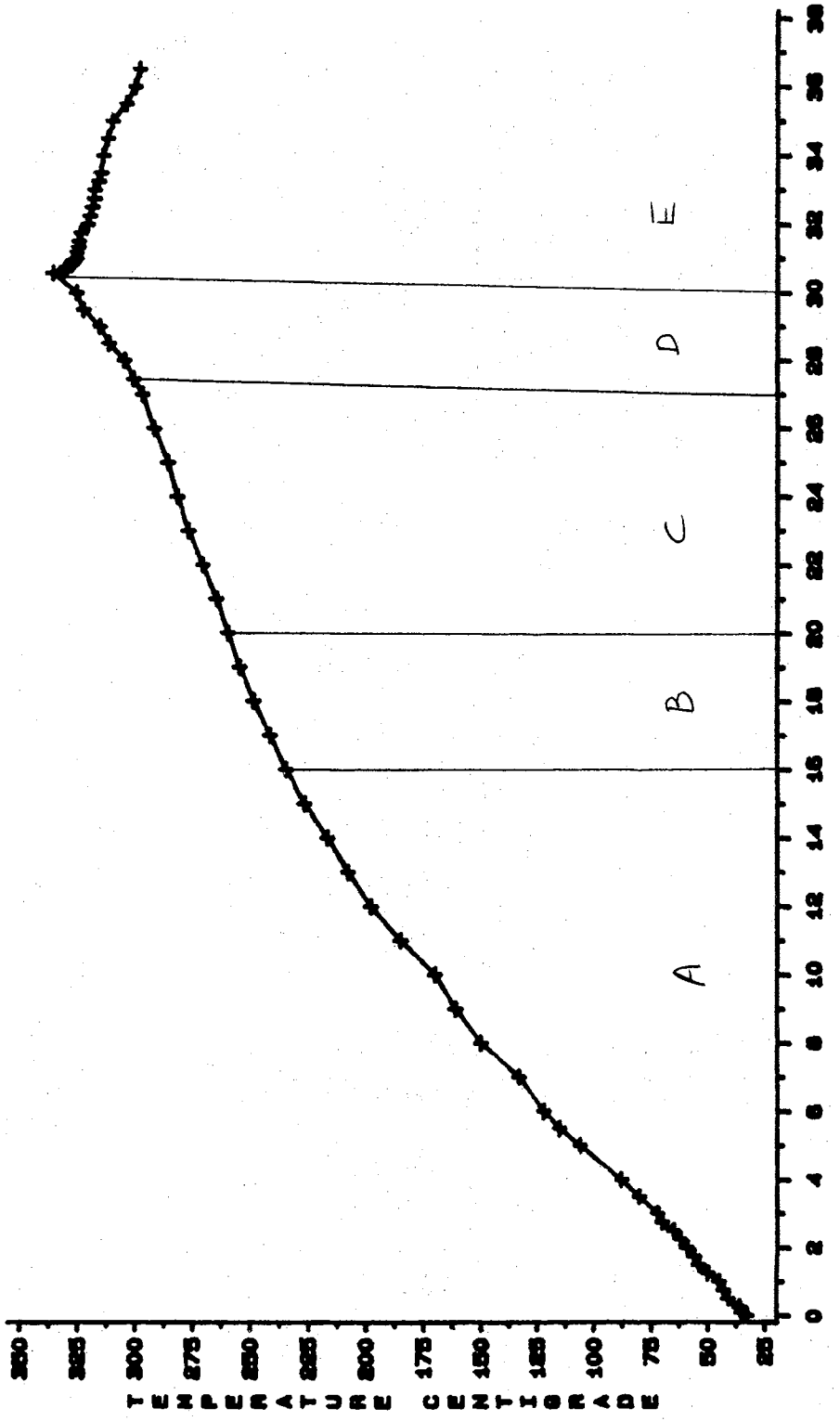

FIGURE 47. TEMPERATURE PROFILE NO.4 SECONDARY CHAMBER WALL (RUN #6)

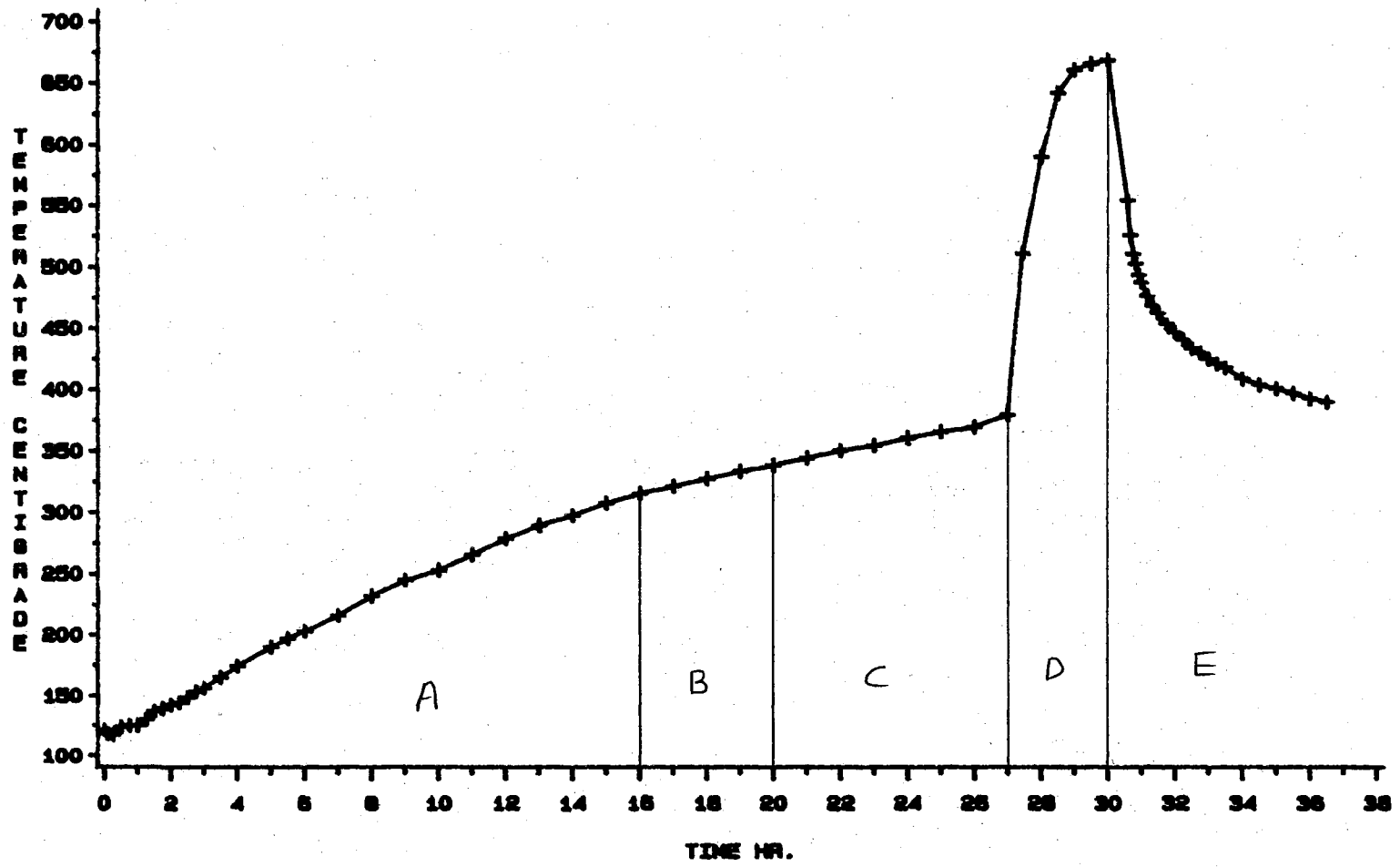

FIGURE 48. TEMPERATURE PROFILE NO.5 FLUE GAS(RUN #6)

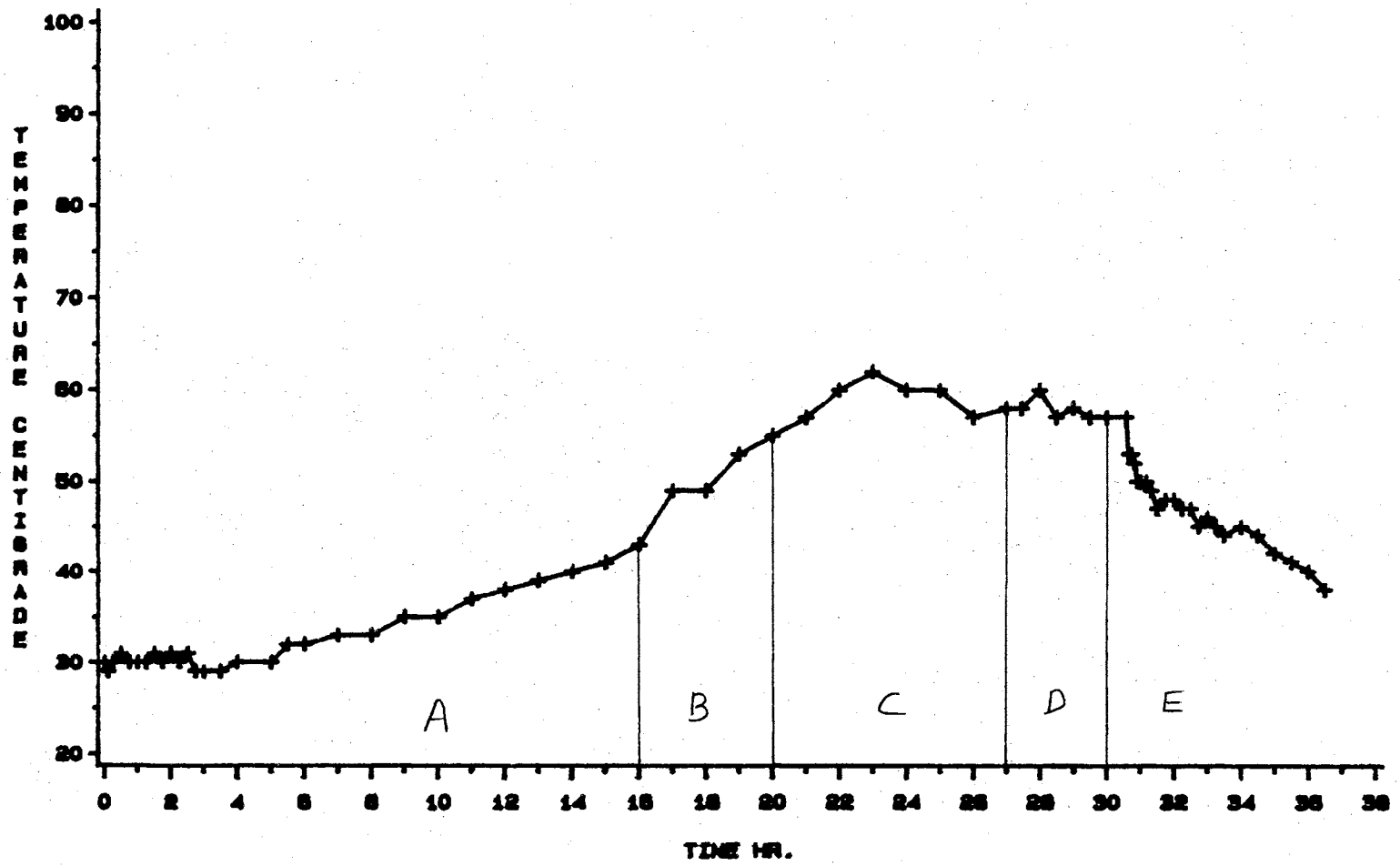

FIGURE 49. TEMPERATURE PROFILE NO.8 SAMPLING PORT WATER(RUN #6)

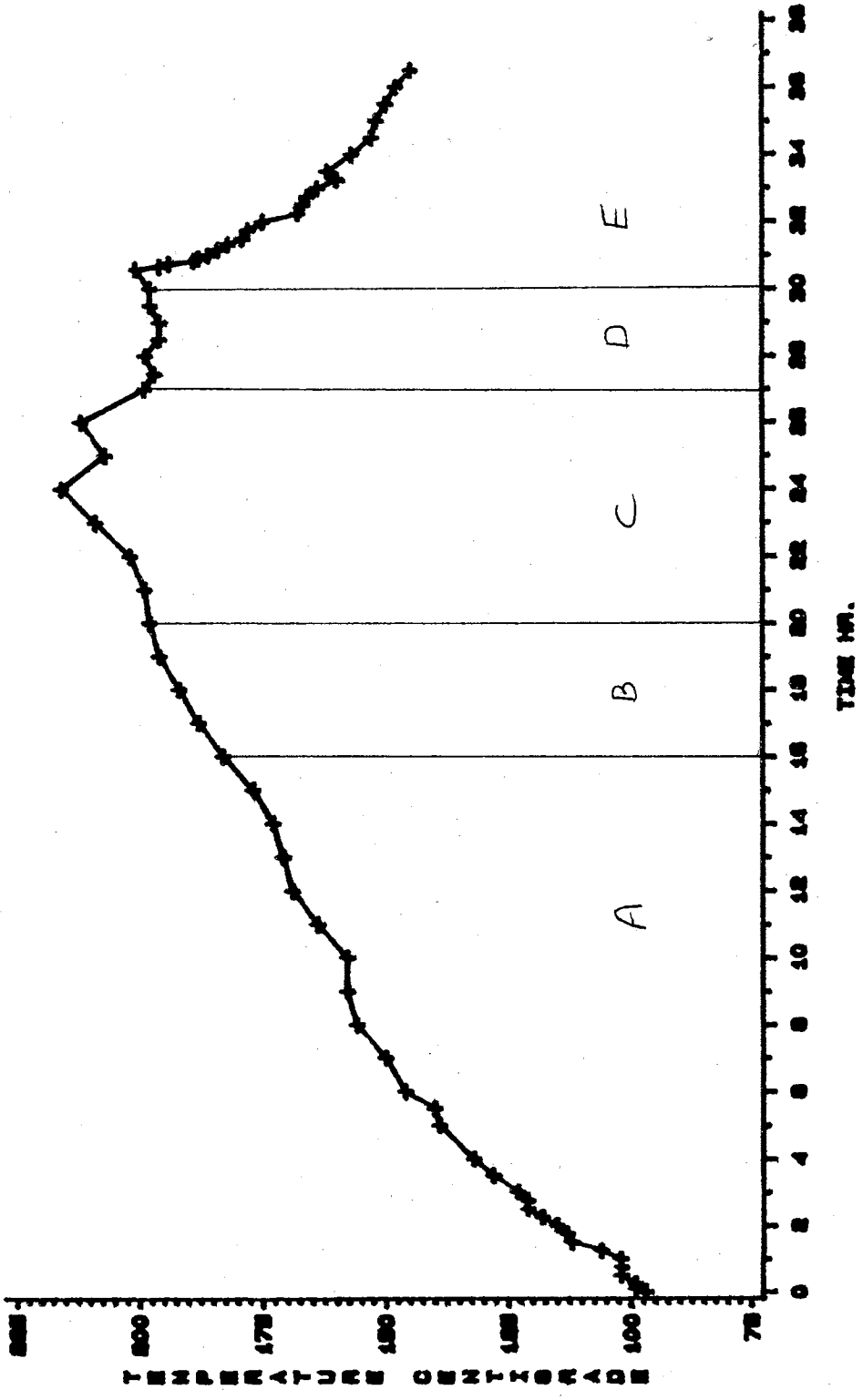

FIGURE 50. TEMPERATURE PROFILE NO.9 AIR HEAT EXCHANGER #1 (RUN #6)

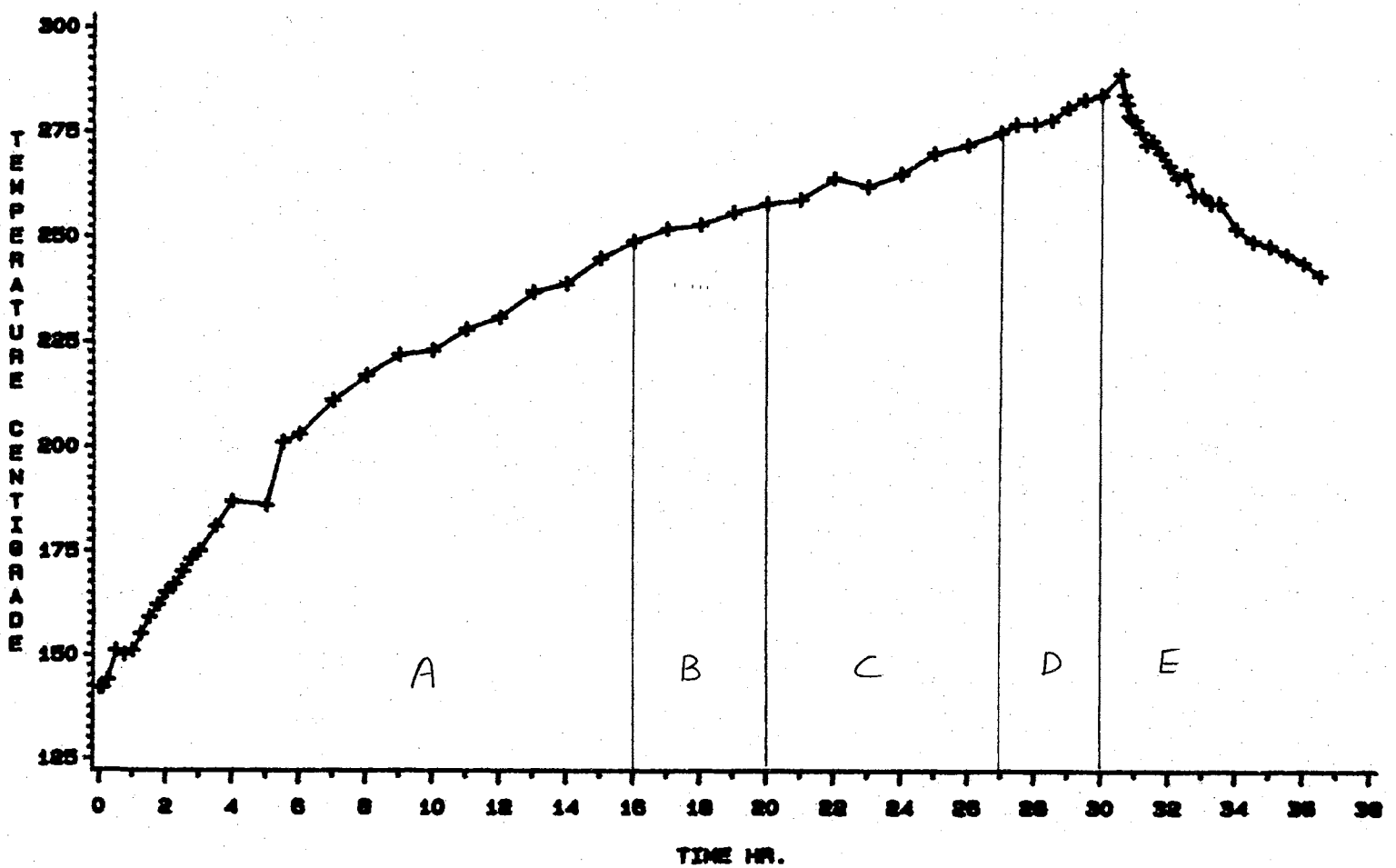

FIGURE 51. TEMPERATURE PROFILE NO.10 AIR HEAT EXCHANGER#2(RUN #6)

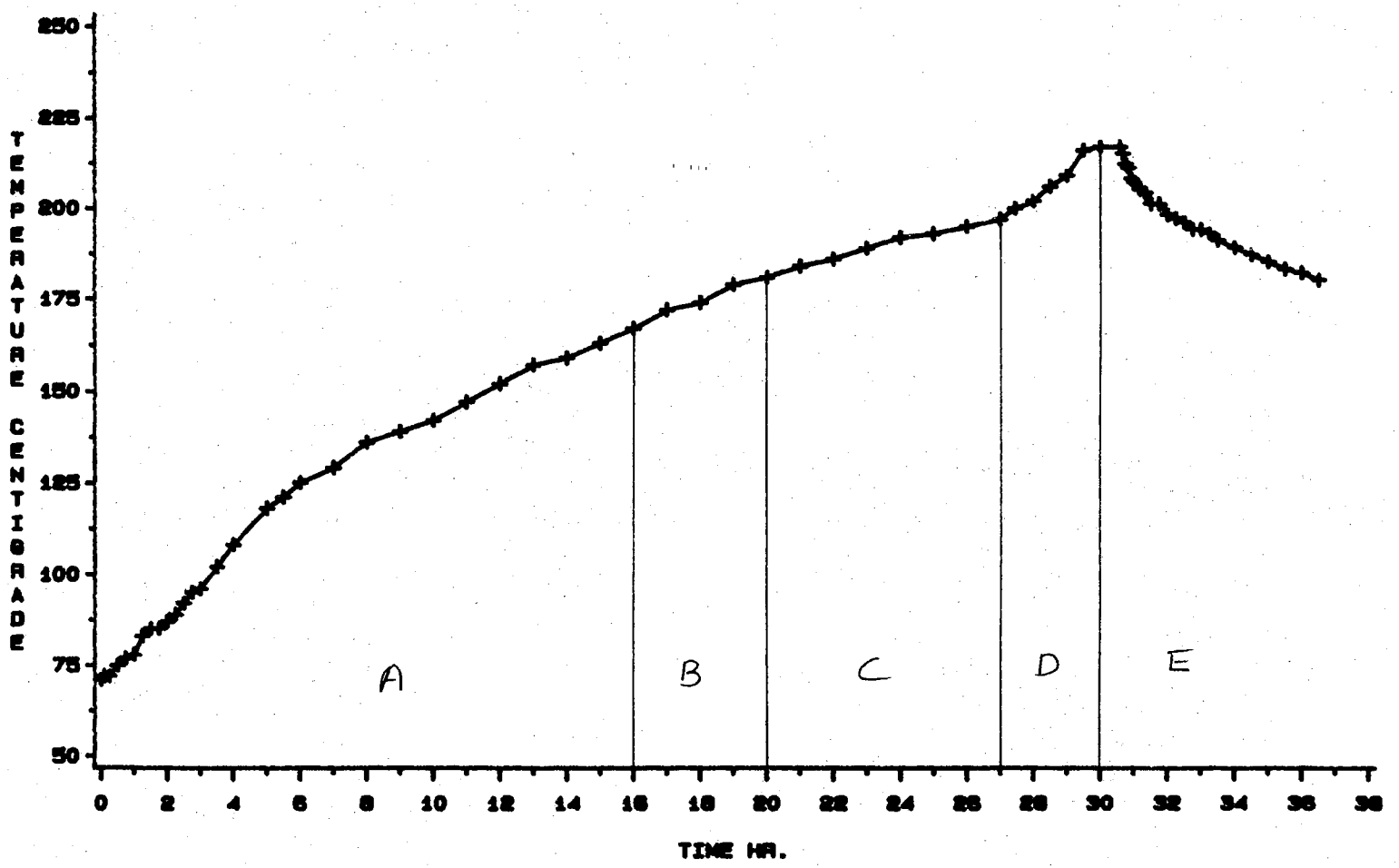

FIGURE 52. TEMPERATURE PROFILE NO.11 AIR HEAT EXCHANGER #3(RUN #6)

primary chamber stabilized and during the last stage of this run it was dropping about 15°C per hour as seen in Figure 44. The flue gas temperature also showed a rapid decrease when the natural gas was turned off but it stabilized during the last part of this run. As in the case of the last run all temperatures started decreasing when the coal was turned on.

Figure 53 shows the flue gas composition. Again it is seen that the O_2 content decreased in flue gas and the CO_2 content increased in the flue gas as more time passed until the 27th hour where a jump in CO_2 content and a huge decrease in O_2 was observed. Once the coal was turned on and natural gas was turned off O_2 increased and CO_2 decreased in flue gas.

This run with coal lasted for 6.5 hours. After the furnace had cooled down, the front door was removed. Ash was found at the bottom of the primary chamber. This time slag samples were also found on the water sampling port. The slag was brown on the outside and black in the inside. It was brown on the outside due to the ash that stick it self to the slag when it was in the molten form. Deposits were also found on the air cooled heat exchangers. On the first heat exchanger the deposit was black and was covered with black dust which was most probably fly ash. The second heat exchanger was covered with brown dust. The third heat exchanger had black deposits on it. The black

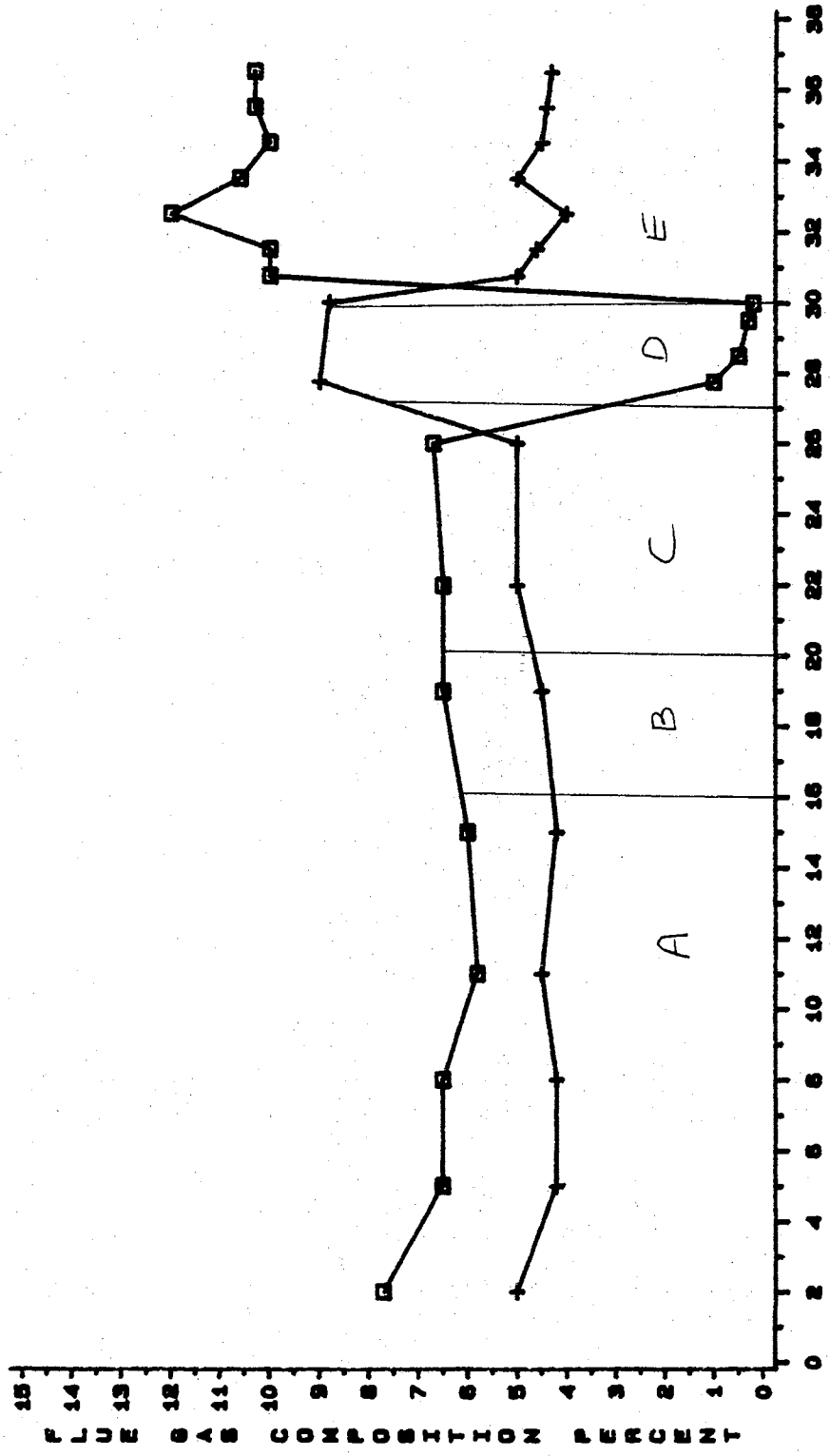

FIGURE 53. FLUE GAS COMPOSITION(RUN #6)

deposits were probably unburned carbon. The average thickness of these layers was 0.1 cm.

The main objective of this run was to check if the furnace could be operated using coal for long runs and it was determined that it is possible to operate the furnace for longer periods of times using coal. This time the same phenomena of increase in temperature was observed but after 27 hours. Deposits on the air cooled heat exchangers looked identical to the deposits observed in the prior run. Another important finding was the air preheating is essential to attain maximum temperature in the primary chamber.

General Discussion

After making six runs, many characteristic behaviors that were associated with this furnace became obvious. In all the runs the furnace inputs were kept as similar as possible. Flow rates of the natural gas, the primary air, the secondary air and the cooling air were kept nearly identical in all runs. Tertiary air flow rate was different only changed in run no.1 and run no.4.

The highest temperature zone in the furnace was in the primary chamber. Maximum temperature achieved in this zone was 1015°C. The temperature in the primary chamber increased till around 950°C in the runs in which near steady state conditions were achieved. The ignition

temperature for coal is around 500°C. Hence in the primary chamber, the temperature can easily be attained for the combustion of coal. The theoretical adiabatic temperature was calculated to be 2200°C.

The second highest temperature zone in the furnace was in the throat region that connected the primary chamber and the secondary chamber. The maximum temperature achieved in this zone was 897°C. In all steady state runs the temperature was more than 800°C in this region. In the secondary chamber, the temperature was higher in the upper region and decreased in the lower region. The thermocouple that read the temperature of the secondary chamber was located after the first heat exchanger, therefore the temperature reading was obtained for the region passed the first heat exchanger. The maximum temperature observed in this region was 704°C. In every steady state run the temperature was more than 575°C. A sudden jump in flue gas temperature was observed in three runs. In run no.2 and run no.4, this took place in the earlier stages. A comparison of the increase in the flue gas temperature for these two runs is shown in Figure 54. In these two runs the combustion conditions were very similar. Almost the same pattern is observed in these runs for flue gas temperature during the early stages except the increase in flue gas temperature happened earlier in run no.4 than in run no.2. This was due to the fact that the furnace was

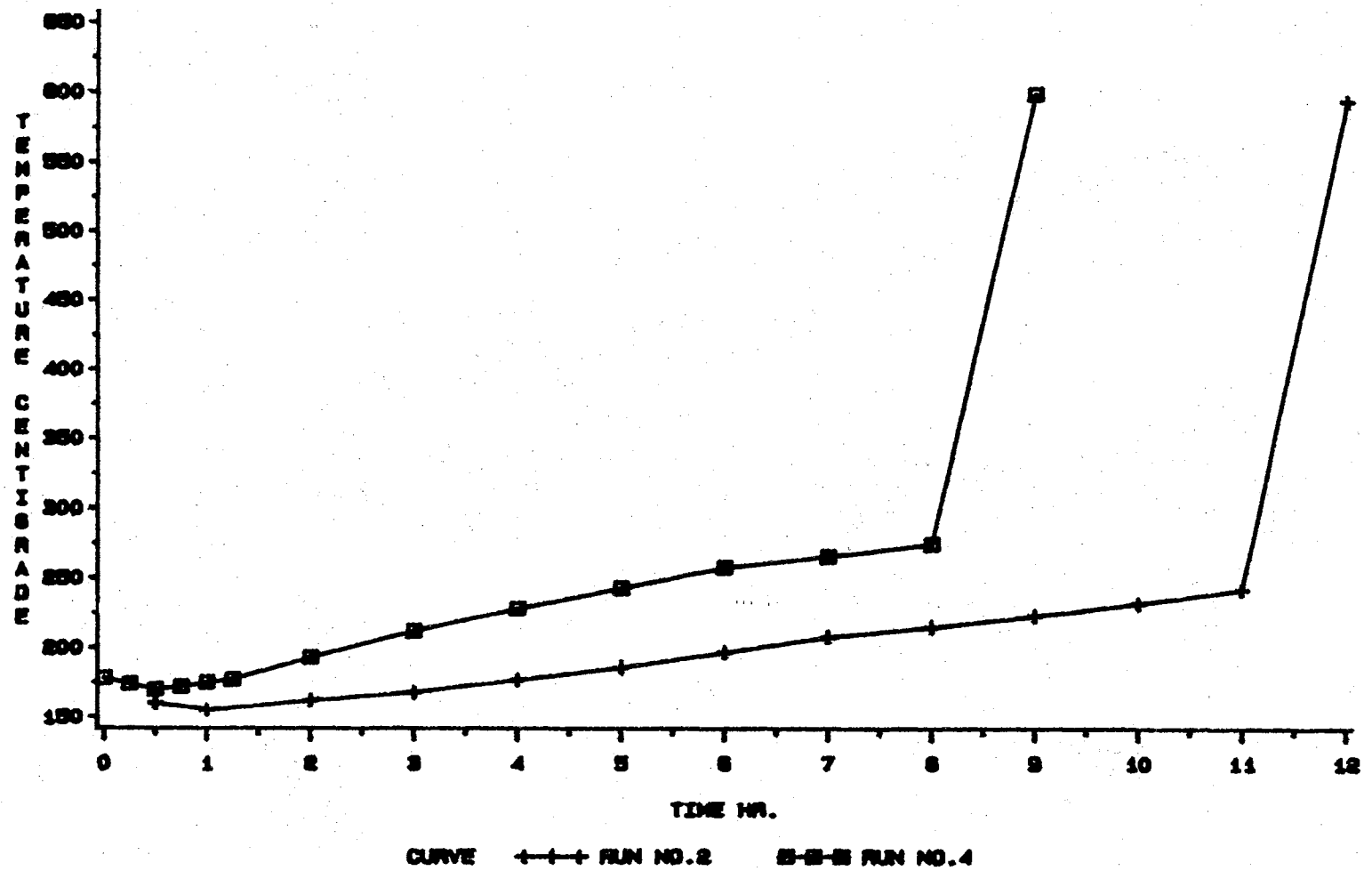

FIGURE 54. FLUE GAS TEMPERATURE COMPARISON FOR RUN #2 AND RUN #4

much hotter in run no.4 than in run no.2, when these runs were started. In run no.6, the same increase was observed but after 27 hours. This was probably due to the fact that the furnace was opened for an inspection after the previous run which changed the combustion environments where as the furnace was not opened between run no.2 and run no.4. The back port of the furnace was taken out after the end of each run. An interesting observation was made that for the runs in which a sudden increase in the flue gas temperature was observed, the back wall of the secondary chamber was red hot. What happened during these runs was that after a little while, the inside wall temperature of the whole furnace became very hot. At some stage the temperature of the region through which the flue gas passed became much hotter than the ignition temperature of CO which is 650°C. This caused the ignition of CO. Before this happened the main reactions that took place in the furnace were:

$$CH_4 + 2\ O_2 \longrightarrow CO_2 + 2\ H_2O \qquad (1)$$

$$CH_4 + 1.5\ O_2 \longrightarrow CO + 2\ H_2O \qquad (2)$$

When the ignition temperature was attained, a new reaction took place at the back region of the furnace. The reaction is given by:

$$2\ CO + O_2 \longrightarrow 2\ CO_2 \qquad (3)$$

Reaction 3 is also exothermic hence the total heat of combustion released in the furnace increased after this reaction took place. This was the reason why there was a sudden increase in the flue gas temperature. The reason this reaction did not take place in the secondary chamber was because the air cooled heat exchangers in the secondary chamber which kept the temperature in this chamber below the ignition temperature of CO. Energy calculations were done for the region where this reaction took place. The exit flue gas temperature assuming adiabatic conditions was found to be 1150°C. This supports the hypothesis that has been presented above. The calculations can be found in appendix B.

The air cooled heat exchangers were found to be very efficient. Air coming out of the second heat exchanger was at higher temperature than the air coming out of the other two heat exchangers. The reason being that the first heat exchanger was smaller than the second heat exchanger, less heat was transferred from this heat exchanger.

Steady state conditions were achieved after 28 or more hours. The initial impression that it would take around six hours to achieve steady state conditions was proven wrong. After the initial ignition, the combustion air had to be preheated to a high temperature and the damper controlling the flue gas had to be opened all the way for optimum combustion. Another pattern that was observed in

these runs was that when the cleaning port was put back, there was a temperature drop in the throat and in the secondary chamber with the temperature in the primary chamber remaining unaffected. A good explanation for this would be that the flame in the primary chamber was divided into two parts because of the arch in the chamber. Combustion air came directly at the first part of flame. When the block was replaced, the second part of the flame was affected more because of a change in the air flow rate coming in through the block than the first part of the flame which affected the throat temperature. The thermocouple in the primary chamber measured the temperature of the first part of the flame hence it did not show any effects compared to the temperatures in the throat which then affected the temperature in the secondary chamber.

Another fact worth noticing from the temperature profiles was that when the flue gas temperature increased, the temperatures in the primary chamber, in the throat and in the secondary chamber decreased for a short time. This was due to a change in the system conditions which affected the combustion in the primary chamber.

To burn coal, coal particles had to be uniform and very fine in order to have a continuous flow. The furnace was operated for long time using coal. Initially when coal was turned on, a large temperature drop was observed

through the furnace. As time passed this drop became smaller. It can be concluded from these runs that the furnace can be operated for at least 10 hours if the furnace has been heated well enough. Slagging and fouling samples were also obtained when coal was used.

CHAPTER IV

MATERIAL AND ENERGY BALANCE

This chapter deals with the material balance and the energy balance for the runs that achieved steady state conditions. Before discussing the results one has to keep in mind the sources of errors that were involved in these runs.

It was very difficult to keep the air flow rates for the combustion air and the cooling air constant. Every time the compressor of the main building turned off, there was a change in air flow rates of 10 to 15%. The same problem was observed in the water flow rate for the sampling port in the primary chamber. Also there was no way to calibrate the gas meter for the natural gas and it was assumed that the flow rate obtained from this meter was accurate. The flow of natural gas also varied during these runs.

The flue gas was analyzed by Orsat meters but these Orsat meters did not provide information about CO content in the flue gas. This problem was solved by using gas chromatography. Since this type of facility did not exist in the laboratory where the experiment was carried out, flue gas samples were collected in gas sampling bags

and then taken to the Engineering North laboratory for the analysis. Due to operating constraints, the time lag between when the samples were taken and when they were analyzed was more than two days. Another important source of error was an inaccurate measurement of water vapor, originally the flue gas contained water vapor but when the flue gas was stored in the sample bag, water vapor condensed. Therefore the flue gas composition obtained from gas chromatography did not provide information about water content of the flue gas. For the purpose of material balance, theoretical amounts of water formed were used.

Another important source of error was a lack of measurement on air leakage into the furnace. It was known for sure that there was air leakage but there was no way to determine the exact amount of leakages at each location.

When calculating energy balances there was one major problem. It was obvious that there was not much heat loss from the furnace due to radiation but there was definitely heat loss due to conduction. The outside wall temperature was not uniform and the temperature varied at different locations. Therefore, temperature measurements of the outside wall were taken at many locations and an average was used as an approximation. A similar problem was faced for the inside wall temperature. The only

inside wall temperature that was known was the lower wall temperature of the secondary chamber. In this case also a good approximation was used.

The above mentioned sources of errors are only a few of the more obvious sources of errors. Sample calculations can be found in appendix B. Table VI shows the material balances and the energy balances for run numbers 4 through 6 using natural gas. The percent error shown in this table was calculated using the formula given below.

$$\text{Error\%} = \frac{\text{Theoretical } CO_2+CO - \text{Calculated } CO_2+CO}{\text{Theoretical } CO_2+CO} \qquad (1)$$

In run number 4 there was no CO formed after the system achieved steady state conditions. The estimated heat loss from the furnace was minimum during run number 4. This result is also supported by the temperature data for this run. The highest temperature observed for all the runs was in run number 4. After this run the furnace was opened for inspection which changed the combustion situation for the next runs and also changed the heat leakage.

The coal used in the last two runs was Clovis Point. An analysis of this coal is given in Table VII. In the

TABLE VI

MATERIAL BALANCES AND
ENERGY BALANCES

Lb.Mole Hr.	Run #4	Run #5	Run #6
CH_4[1]	0.233	0.260	0.280
Flue Gas			
CO_2[2]	0.182	0.198	0.298
CO[3]	-	0.110	0.055
O_2[2]	1.220	1.380	1.240
N_2[4]	4.600	5.200	4.660
H_2O[5]	0.412	0.520	0.520
Air[4] Leakage	7.320	8.120	7.590
%Error	21.880	18.400	26.070
Heat Loss[6] Btu.Hr.	18080	53260	40600

1. Measured using dry gas meter.
2. Measured using Orsat meter.
3. Measured using gas chromatography.
4. Calculated by material balance.
5. Calculated based on methane content.
6. Calculated by energy balance.

TABLE VII

COAL ANALYSIS
ULTIMATE

	Weight%		
	As Recd.	Dry	Air Dry
Moisture	26.93	0.00	18.23
Carbon	49.09	67.19	54.94
Hydrogen	3.57	4.89	4.00
Nitrogen	0.75	1.03	0.84
Sulfur	0.32	0.44	0.36
Ash	5.65	7.73	6.32
Oxygen	13.69	18.72	15.31
Heating Value Btu.Lb.	8367	11450	9363

Source: Hazen Research, Inc.

last run the total amount of coal used was 19.5 lbs. and the total ash collected in the primary chamber was 0.45 lbs. This implies that 0.65 lbs. of ash escaped as a fly ash to the secondary chamber. Looking at the sources of errors and the percent error obtained for each run, the results seem to be quite good.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The most important conclusion from this research was that the furnace can be operated using natural gas and coal. Many changes, corrections and modifications were made to this furnace before it supported combustion with natural gas and coal. New equipment like an orfice meter, orsat meters, gas meters, preheaters, insulation for preheaters and thermocouples were added to the already existing equipment.

Initial ignition of the furnace was a very dangerous process as most of the time the flame came out of the sampling port on ignition. One has to be very careful in lighting up the furnace. The most delicate part is the initial ignition process and when the cleaning port is replaced. Any mistake in this process would cause the flame to go out. The hotter the furnace, the easier it was to light it up. Once the furnace was lit, the combustion environment inside the furnace depended on the preheating of the combustion air and the induced draft fan. The combustion air should be preheated as high as possible and the damper controlling the induced draft fan should be fully open for optimum combustion conditions.

There was a large amount of air leakage into the furnace and it was impossible to control this leakage. In three runs, a sudden increase in the flue gas temperature was observed. In the beginning it was feared that the stack and the induced draft fan would not be able to withstand such high temperatures but it was found that the stack and the induced draft fan can stand these high temperatures. The increase in the flue gas temperature occurred when the back portion of the furnace through which the flue gas exits becomes hotter than the ignition temperature of CO and this cause the ignition of CO in the flue gas to form CO_2.

On average it took more than 28 hours for the conditions in the furnace to achieve steady state conditions using natural gas. Once the steady state conditions were achieved, the temperature in the primary chamber was found to be high enough to support combustion of coal. The maximum temperature observed in the primary chamber was 1015°C. This temperature is very comparable to the temperatures observed in the industrial boilers. The theoretical adiabatic temperature was calculated to be 2200°C. For coal runs, coal had to be ground to 20 mesh or less to have a continuous flow in the furnace. Actually coal size should be even smaller than this but the only facility to only grind coal was limited to 20 mesh. The furnace was operated for 6.5 hours using coal

during the final run. Based on temperature limitations it was concluded that the furnace can be operated for at least 10 hours using coal under pseudo steady state conditions. Slagging and fouling took place when coal was used as a fuel. Slag samples were found in the primary chamber at the end of run number 6. Fouling samples were found in the secondary chamber at the end of run number 5 and 6. These fouling samples are shown in Figure 39-44.

Thus in this research after making many changes and adding new equipment, the furnace has been made operative with coal. Slag samples and fouling samples have been preserved for future study.

CHAPTER VIII

RECOMMENDATIONS

Although many changes and modifications have been made on the existing facility. There is still room for more changes, modifications and new equipment which would improve the overall quality of the existing facility.

The way the gas burners and the combustion air inlets are located, causes the flame in the primary chamber to go out when the air flow rate is very strong in the primary chamber. The natural gas, the primary air and the secondary air enter the primary chamber from the top and the tertiary air comes in from the side. The natural gas burners location should be changed so that the natural gas enters horizontally in the lower level of the primary chamber. This will serve two purposes. The flame would become more stable and the ignition process would be more safe.

More thermocouples should be added to the facility to provide more information on the temperature profiles of the inside wall and the outside wall of the furnace, the primary chamber, the secondary chamber and the flue gas in the stack. This information would help in energy balances. Gaskets made of a material that can withstand high

temperatures should be added to all the places where there is a possibility of air leakage, to minimize this leakage and also to reduce heat loss from the furnace. The sampling ports for collecting slagging and fouling samples should be redesigned so that minimum amount of samples is lost due to brushing against the furnace walls when the sampling port is taken out.

A compressor should be installed in the laboratory for the combustion and the cooling air so that there is no variations in air flow rates especially in the initial part of the ignition process.

An Orsat meter that can measure carbon monoxide content in the flue gas is needed to provide further information for the material balances. If possible, a gas chromatograph equipment should be set up in the laboratory so that the flue gas samples can be analyzed as soon as they are collected. A wet bulb thermometer should also be installed in the stack to provide information on water vapor content in the flue gas. There are three observation holes in the furnace. Only one observation hole of these three is useful and it is located in the front of the primary chamber. The other two observation holes do not serve any purposes. There locations should be changed to make them more useful or they should be closed to prevent unnecessary leakage of air. One of the observation holes which is located at the side of the primary chamber can

also be used to place the fire wick in the primary chamber for ignition.

The air hoses that carry hot air from the heat exchangers in the secondary chamber can not handle high temperatures around 300°C. They should be replaced by hoses that can withstand high temperatures. The design of the outlet of the chimney should be altered so that water may not enter the stack when it rains. This problem was faced during the furnace operation.

A grinder is needed which can grind the coal to 20 mesh or less in short period of time. The existing grinder takes about two days to grind 30 lbs of coal. A very important modification that needs to be implemented as soon as possible is to place the coal feeder as near as possible to the furnace, preferably on the top of the furnace so that the coal flow could be smooth and continuous. Presently the coal feeder is located at some distance from the furnace. The coal is passed into the furnace through a long pipe which is bend at different locations. Coal flow gets hindered at sometimes which is very damaging to the on going experiment.

The furnace needs to be open after each long run for inside cleaning. This is very damaging to the furnace to the furnace. Some additions should be made in the furnace so that the furnace can be cleaned without having to open it. After running the furnace with coal for six or seven

runs, it is for sure that lot of soot will accumulate in the stack. An intensive cleaning of the stack would be required. The way the stack is designed now, it will be necessary to take apart the whole stack and then clean it. Some redesigning should be done to avoid the tedious process of opening the whole stack to clean it.

The recommendations discussed above are a few of the major changes that should be implemented to improve the overall quality of the existing facility.

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APPENDIX A

RAW DATA

TABLE VIII

CALIBRATION DATA FOR WATER ROTAMETER

Rotameter G.P.M.	Volume Collected Gal.	Time Sec	Volumetric Rate G.P.M.
1-0.95	0.62	0.36	1.72
	0.62	0.36	1.72
	0.83	0.50	1.65
2-1.98	0.73	0.26	2.80
	0.71	0.26	2.76
	0.74	0.27	2.77
3.0	0.74	0.18	4.18
	0.72	0.18	4.09
	0.81	0.20	4.13
3.4	0.68	0.12	5.52
	0.68	0.13	5.52

TABLE IX

CALIBRATION DATA FOR COAL FEEDER

Feeder Setting	Mass lbm	Time Hr.	Mass Flow Rate lbm per Hr.
1	0.47	0.83	0.56
	0.82	1.00	0.82
	0.58	1.00	0.58
2	0.65	0.58	1.11
	1.40	1.00	1.40
	1.34	1.00	1.34
	1.38	1.00	1.38
	1.36	1.00	1.36
3	1.46	0.50	2.92
	1.24	0.50	2.48
	1.26	0.50	2.52
	1.24	0.50	2.48
4	1.85	0.50	3.70
	1.85	0.50	3.70
	1.86	0.50	3.72
	1.86	0.50	3.72
5	1.28	0.25	5.12
	1.28	0.25	5.12
	1.30	0.25	5.20
	1.28	0.25	5.12
6	1.60	0.25	6.40
	1.62	0.25	6.80
	1.60	0.25	6.40
	1.62	0.25	6.80

TABLE X

CALIBRATION DATA FOR ROTAMETER FOR PRIMARY AIR USING WET TEST METER

Rotameter Setting Cu.Ft.Min	Volume Measured Cu.Ft.	Time Min.	Volumetric Flow Rate Cu.Ft.Min
1.0	6.05	5.00	1.21
	6.00	5.00	1.20
1.5	8.70	5.00	1.74
	8.35	5.00	1.67
2.0	11.25	5.00	2.25
	10.95	5.00	2.19
2.5	13.80	5.00	2.76
	13.60	5.00	2.72

Pressure = 742 mm Hg
Room Temperature = 26°C
Water Temperature = 25°C

TABLE XI

CALIBRATION DATA FOR ROTAMETER FOR PRIMARY AIR GAS METER

Rotameter Setting	Volume Measured Cu.Ft.	Time Min.	Volumetric Flow Rate Cu.Ft.Min.
1.0	6.70	5.00	1.34
	6.10	5.00	1.22
1.5	8.60	5.00	1.72
	8.30	5.00	1.66
2.0	10.90	5.00	2.18
	10.90	5.00	2.18
2.5	13.00	5.00	2.62
	13.20	5.00	2.64
3.0	14.90	5.00	2.98
	14.90	5.00	2.98

Pressure = 743 mm Hg
Room Temperature = 27°C

TABLE XII

CALIBRATION DATA FOR ROTAMETER FOR SECONDARY AIR USING WET TEST METER

Rotameter Setting	Volume Measured Cu.Ft.	Time Min.	Volumetric Rate Rate Cu.Ft.Min.
1.0	5.95	5.00	1.19
	5.90	5.00	1.18
1.5	9.10	5.00	1.82
	9.15	5.00	1.83
2.0	11.62	5.00	2.32
	12.50	5.00	2.50
2.5	15.60	5.00	3.12
	15.80	5.00	3.16
3.0	19.20	5.00	3.84
	19.40	5.00	3.88
3.5	22.50	5.00	4.50
	21.80	5.00	4.36

Pressure = 744 mm Hg
Room Temperature = 26°C
Water Temoerature = 24°C

TABLE XIII

CALIBRATION DATA FOR ROTAMETER FOR TERTIARY AIR USING WET TEST METER

Rotameter Setting	Volume Measured Cu.Ft.	Time Min.	Volumetric Flow Rate Cu.Ft.Min.
1.0	6.50	5.00	1.30
	6.50	5.00	1.30
1.5	8.40	5.00	1.68
	8.80	5.00	1.76
2.0	11.10	5.00	2.22
	11.25	5.00	2.25
2.5	13.80	5.00	2.76
	14.10	5.00	2.82
3.0	16.65	5.00	3.33
	16.60	5.00	3.32
3.5	19.60	5.00	3.92
	19.50	5.00	3.90

Pressure = 744 mm Hg
Room Temperature = 26°C
Water Temperature = 24°C

RUN #1 USING NATURAL GAS

Pressure = 746 mm Hg
Room Temperature = 23°C
Natural Gas Flow Rate = 1.5 Cu.Ft.Min.
Primary Air Flow Rate = 1.9-2.2 Cu.Ft.Min.
Secondary Air Flow Rate = 1.8-2.2 Cu.Ft.Min.
Tertiary Air Flow Rate = 2.2-2.5 Cu.Ft.Min.
Cooling Air Flow Rate = 9.0 Cu.Ft.Min.
Cooling Water Flow Rate = 1 G.P.Min.
Int. Orfice Meter Pressure Drop = 0.6 Inch. of Water
Fin. Orfice Meter Pressure Drop = 0.2 Inch. of Water
Air Inlet Temperature = 21°C
Water Inlet Temperature = 20°C
Flame Color = Blue

TABLE XIV

TEMPERATURE PROFILES (RUN #1)
(Centigrade)

Thermocouple #	Time (Hr.) 3	5	6.5	7	8.5
1	781	793	748	749	759
2	644	689	614	623	651
3	468	493	438	445	465
4	129	140	143	147	157
5	220	236	223	227	239
6	380	390	382	373	364
7	363	370	362	356	360
8	-	-	22	22	23
9	-	-	110	110	117
10	-	-	169	173	182
11	-	-	100	106	110

Orsat Reading at the end: CO_2 = 3%
O_2 = 13%

RUN #2 USING NATURAL GAS

Pressure = 744 mm Hg
Room Temperature = 29°C
Natural Gas Flow Rate = 1.5 Cu.Ft.Min.
Primary Air Flow Rate = 2.0-2.2 Cu.Ft.Min.
Secondary Air Flow Rate = 2.0-2.2 Cu.Ft.Min.
Tertiary Air Flow Rate = 2.0-2.2 Cu.Ft.Min.
Cooling Air Flow Rate = 9.0 Cu.Ft.Min.
Cooling Water Flow Rate = 1 G.P.Min.
Int. Orfice Meter Pressure Drop = 0.6 Inch. of Water
Fin. Orfice Meter Pressure Drop = 0.2 Inch. of Water
Air Inlet Temperature = 20°C
Water Inlet Temperature = 22°C
Flame Color = Blue

TABLE XV

TEMPERATURE PROFILES (RUN #2)
(Centigrade)

Thermocouple #	Time (Hr.) 0.5	1	2	3	4
1	670	687	727	727	757
2	451	444	470	497	526
3	328	320	334	351	366
4	89	90	94	99	105
5	160	155	162	168	177
6	331	355	351	346	344
7	325	361	348	347	349
8	27	27	26	25	26
9	87	81	86	91	98
10	136	130	132	139	144
11	75	75	78	81	86

TABLE XV (Continued)

Thermocouple #	Time(Hr.) 5	6	7	8	9
1	767	766	772	765	770
2	553	580	602	609	628
3	388	402	421	424	439
4	112	120	128	134	141
5	186	197	208	215	223
6	342	342	339	347	348
7	346	345	344	346	349
8	27	26	27	26	26
9	103	106	112	117	121
10	151	156	162	168	173
11	91	92	100	103	105

TABLE XV (Continued)

Thermocouple #	Time(Hr.) 10	11
1	770	771
2	646	660
3	451	472
4	148	160
5	232	242
6	345	342
7	349	348
8	27	28
9	125	131
10	181	190
11	112	118

TABLE XVI

ORSAT METER READING (RUN #2)
(Percent)

Gas	Time(Hr.)			
	3	9	10	11
CO_2	2.50	2.55	2.55	4.00
O_2	13.00	11.00	10.95	9.00

RUN #3 USING NATURAL GAS

Pressure = 745 mm Hg
Room Temperature = 20°C
Natural Gas Flow Rate = 1.5 Cu.Ft.Min.
Primary Air Flow Rate = 2.0 Cu.Ft.Min.
Secondary Air Flow Rate = 2.0 Cu.Ft.Min.
Tertiary Air Flow Rate = 2.0 Cu.Ft.Min.
Cooling Air Flow Rate = 9.0 Cu.Ft.Min.
Int. Orfice Meter Pressure Drop = 0.6 Inch. of Water
Fin. Orfice Meter Pressure Drop = 0.2 Inch. of Water
Cooling Water Flow Rate = None
Air Inlet Temperature = 20°C
Water Inlet Temperature = ---
Flame Color = Blue

TABLE XVII

TEMPERATURE PROFILES (RUN #3)
(Centigrade)

Thermocouple #	Time (Hr.) 0.00	0.25	0.50	0.75	1.00
1	596	602	635	648	652
2	421	403	405	410	414
3	304	281	280	280	282
4	41	44	44	46	48
5	127	119	116	116	118
6	246	329	344	353	359
7	221	343	363	368	371
8	-	-	-	-	-
9	78	68	66	67	68
10	131	120	109	106	105
11	71	61	60	60	59

TABLE XVII (Continued)

Thermocouple #	Time (Hr.) 1.25	1.50	1.75	2.00	2.25
1	658	668	677	682	686
2	418	424	431	443	449
3	285	288	291	298	302
4	48	50	51	53	55
5	119	120	122	124	126
6	364	363	364	364	365
7	374	373	374	372	374
8	-	-	-	-	-
9	67	68	68	69	70
10	104	104	105	106	106
11	59	59	61	59	62

TABLE XVII (Continued)

Thermocouple #	Time (Hr.) 2.50	2.75	3.00	3.50	4.00
1	690	690	695	694	690
2	457	465	474	490	505
3	307	311	316	324	336
4	56	57	60	62	67
5	127	130	131	136	141
6	356	355	357	359	369
7	366	363	365	368	377
8	-	-	-	-	-
9	70	71	73	78	79
10	108	110	113	115	122
11	62	63	64	66	69

TABLE XVII (Continued)

Thermocouple #	Time (Hr.) 4.50
1	684
2	515
3	339
4	71
5	144
6	367
7	375
8	-
9	81
10	121
11	70

TABLE XVIII

ORSAT METER READING (RUN #3)
(Percent)

Gas	Time(Hr.) 1	3
CO_2	2	2
O_2	14	13

RUN #4 USING NATURAL GAS

Pressure = 749 mm Hg
Room Temperature = 22°C
Natural Gas Flow Rate = 1.5 Cu.Ft.Min.
Primary Air Flow Rate = 2.0 Cu.Ft.Min.
Secondary Air Flow Rate = 2.0 Cu.Ft.Min.
Tertiary Air Flow Rate = 2.5 Cu.Ft.Min.
Cooling Air Flow Rate = 9.0 Cu.Ft.Min.
Cooling Water Flow Rate = None
Int. Orfice Meter Pressure Drop = 0.6 Inch. of Water
Fin. Orfice Meter Pressure Drop = 0.2 Inch. of Water
Air Inlet Temperature = 22°C
Water Inlet Temperature = ---
Initial Flame Color = Blue
Final Flame Color = Reddish Yellow

TABLE XIX

TEMPERATURE PROFILES (RUN #4)
(Centigrade)

Thermocouple #	Time (Hr.) 0.00	0.25	0.50	0.75	1.00
1	618	625	671	715	726
2	550	545	508	517	534
3	410	397	380	383	393
4	110	112	113	113	114
5	178	174	170	172	175
6	0	17	278	330	340
7	0	18	244	325	341
8	-	-	-	-	-
9	112	105	96	93	95
10	172	162	160	158	160
11	104	98	92	86	86

TABLE XIX (Continued)

Thermocouple #	Time (Hr.) 1.25	1.50	1.75	2.00	2.50
1	743	754	756	763	776
2	551	570	603	624	663
3	403	414	430	443	461
4	115	117	119	120	123
5	177	183	188	193	202
6	340	344	345	347	353
7	342	350	350	352	356
8	-	-	-	-	-
9	98	101	105	112	115
10	163	167	172	177	187
11	91	92	95	97	102

TABLE XIX (Continued)

Thermocouple #	Time (Hr.) 3.00	3.50	4.00	5.00	6.00
1	781	789	796	820	838
2	698	716	729	750	771
3	479	489	498	513	530
4	128	132	137	148	160
5	212	219	228	243	258
6	360	364	365	369	368
7	363	366	368	371	370
8	-	-	-	-	-
9	126	128	132	141	147
10	196	203	208	218	226
11	109	113	118	126	133

TABLE XIX (Continued)

Thermocouple #	Time (Hr.) 7.00	8.00	9.00	10.00	11.00
1	851	876	829	841	848
2	781	789	784	792	799
3	538	542	529	542	566
4	172	185	199	220	241
5	266	275	600	640	670
6	399	434	430	425	422
7	400	403	430	400	400
8	-	-	-	-	-
9	144	143	151	159	165
10	233	242	245	256	267
11	135	139	153	164	176

TABLE XIX (Continued)

Thermocouple #	Time (Hr.) 12.00	13.00	14.00	15.00	16.00
1	857	867	879	897	908
2	808	818	827	840	829
3	586	593	611	630	631
4	263	284	328	363	385
5	694	716	737	733	733
6	422	412	376	398	375
7	396	389	356	323	310
8	-	-	-	-	-
9	173	175	186	197	207
10	276	283	300	311	304
11	188	199	233	245	254

TABLE XIX (Continued)

Thermocouple #	Time (Hr.) 17.00	18.00	19.00	20.00	21.00
1	925	941	955	967	976
2	825	836	845	851	858
3	627	633	634	637	645
4	394	418	435	445	459
5	744	742	747	754	759
6	292	400	384	383	380
7	246	350	350	350	344
8	-	-	-	-	-
9	227	229	228	226	224
10	308	316	325	329	332
11	256	266	268	270	273

TABLE XIX (Continued)

Thermocouple #	Time (Hr.) 22.00	23.00	24.00	25.00	26.00
1	984	990	998	995	1004
2	865	871	877	876	882
3	653	660	669	673	679
4	473	484	497	513	522
5	763	767	774	783	792
6	380	380	375	373	368
7	344	344	339	337	332
8	-	-	-	-	-
9	224	223	220	219	219
10	336	342	344	346	349
11	278	281	286	289	291

TABLE XIX (Continued)

Thermocouple #	Time (Hr.) 27.00	28.00	29.00	30.00	31.00
1	1011	1015	1007	1008	1008
2	887	894	896	897	897
3	686	690	696	699	701
4	533	532	532	538	541
5	799	792	790	788	787
6	328	332	25	18	19
7	295	302	25	19	19
8	-	-	-	-	-
9	222	223	220	217	216
10	352	354	356	357	359
11	291	294	296	300	299

TABLE XIX (Continued)

Thermocouple #	Time (Hr.) 32.00	32.50	33.00	34.00	35.00
1	1006	1006	1006	995	983
2	896	896	893	888	880
3	702	704	703	702	698
4	545	547	550	549	547
5	784	782	778	760	727
6	19	18	18	17	18
7	19	18	19	19	19
8	-	-	-	-	-
9	215	215	213	212	210
10	354	360	360	360	361
11	301	303	303	306	307

TABLE XX

ORSAT METER READING (RUN #4)
(Percent)

Gas	Time(Hr.)					
	1.0	3.0	6.5	9.0	12.0	15.0
CO_2	4.0	3.1	3.4	8.0	8.5	9.0
O_2	10.0	8.0	6.5	3.0	2.0	1.2

TABLE XX (Continued)

Gas	Time(Hr.)				
	18.0	23.0	28.0	32.5	34.0
CO_2	9.2	8.8	9.0	8.0	7.9
O_2	1.2	0.0	0.0	1.0	1.0

RUN #5 USING NATURAL GAS AND COAL

Pressure = 745 mm Hg
Room Temperature = 21°C
Natural Gas Flow Rate = 1.5 Cu.Ft.Min.
Primary Air Flow Rate = 2.0 Cu.Ft.Min.
Secondary Air Flow Rate = 2.0 Cu.Ft.Min.
Tertiary Air Flow Rate = 2.0 Cu.Ft.Min.
Cooling Air Flow Rate = 9.0 Cu.Ft.Min.
Cooling Water Flow Rate = 0.5 Gal.Per.Min.
Int. Orfice Meter Pressure Drop = 0.5 Inch. of Water
Fin. Orfice Meter Pressure Drop = 0.2 Inch. of Water
Air Inlet Temperature = 23°C
Water Inlet Temperature = 21°C
Initial Flame Color = Blue
Final Flame Color = Reddish Yellow

TABLE XXI

TEMPERATURE PROFILES (RUN #5)
(Centigrade)

Thermocouple #	Time (Hr.) 0.00	0.25	0.50	0.75	1.00
1	580	574	596	616	642
2	446	447	441	447	451
3	327	327	323	328	329
4	101	101	101	102	102
5	140	134	134	135	135
6	18	243	294	310	317
7	18	238	300	150	18
8	41	27	28	28	28
9	68	68	71	73	73
10	139	137	134	134	135
11	80	78	76	77	78

TABLE XXI (Continued)

Thermocouple #	Time (Hr.) 1.25	1.50	1.75	2.00	2.25
1	651	661	677	712	744
2	477	471	481	511	542
3	346	345	351	364	392
4	104	105	105	107	108
5	138	139	139	146	164
6	321	321	323	326	325
7	310	286	323	334	348
8	28	29	29	29	29
9	76	77	79	85	90
10	136	138	139	143	151
11	79	80	82	85	89

TABLE XXI (Continued)

Thermocouple #	Time (Hr.) 2.50	2.75	3.00	3.50	4.00
1	757	771	778	792	796
2	560	568	577	593	617
3	406	413	420	436	448
4	111	113	115	120	124
5	170	175	178	187	196
6	328	329	331	330	330
7	344	343	346	346	351
8	30	32	32	35	37
9	96	95	98	103	106
10	155	160	164	167	175
11	93	95	98	102	111

TABLE XXI (Continued)

Thermocouple #	Time (Hr.) 4.50	5.00	5.50	6.00	7.00
1	807	806	810	817	830
2	645	659	671	694	707
3	462	471	479	486	497
4	130	133	138	146	154
5	205	211	217	226	236
6	332	332	332	332	333
7	348	351	349	350	350
8	40	43	46	48	51
9	119	122	124	126	128
10	184	187	193	197	205
11	113	120	120	122	129

TABLE XXI (Continued)

Thermocouple #	Time (Hr.) 8.00	9.00	10.00	11.00	12.00
1	837	845	857	870	875
2	727	741	750	761	770
3	511	520	531	539	548
4	166	175	184	194	205
5	250	264	272	283	294
6	332	330	328	327	326
7	349	350	348	347	348
8	54	55	56	57	57
9	139	140	144	147	152
10	212	217	222	228	232
11	134	140	144	147	152

TABLE XXI (Continued)

Thermocouple #	Time (Hr.) 13.00	14.00	15.00	16.00	17.00
1	881	884	887	895	902
2	778	783	789	794	798
3	553	557	561	567	569
4	213	222	230	236	242
5	303	312	318	327	332
6	325	380	383	384	385
7	349	360	360	362	360
8	63	33	33	35	35
9	154	156	156	158	160
10	236	239	241	244	247
11	155	158	160	161	165

TABLE XXI (Continued)

Thermocouple #	Time (Hr.) 18.00	19.00	20.00	21.00	22.00
1	906	921	926	930	934
2	802	796	803	807	807
3	574	568	566	568	569
4	249	254	260	265	269
5	339	344	350	355	359
6	384	382	382	381	382
7	361	365	365	365	366
8	38	37	38	38	41
9	163	162	169	174	179
10	250	251	252	255	256
11	168	170	170	173	174

TABLE XXI (Continued)

Thermocouple #	Time (Hr.) 23.00	24.00	25.00	26.00	27.00
1	937	939	948	952	956
2	807	808	808	809	811
3	570	572	572	574	577
4	273	278	283	288	292
5	365	370	374	378	383
6	386	387	392	395	396
7	368	368	370	373	372
8	41	42	45	46	47
9	184	191	195	199	201
10	260	263	267	269	273
11	178	181	184	186	189

Coal Turned On At After 28th Hour = 2.0 Lb.Per.Hr
New Primary Air Flow Rate = 2.0 Cu.Ft.Min.
New Secondary Air Flow Rate = 2.0 Cu.Ft.Min.
New Tertiary Air Flow Rate = 2.5 Cu.Ft.Min.
Primary Air Flow Rate At 30th Hour = 1.5 Cu.Ft.Min.
Tertiary Air Flow Rate At 31st Hour = 3.0 Cu.Ft.Min.
Coal Flow Rate At 32nd Hour = 2.5 Lb.Per.Hr.
Natural Gas Flow Rate At 32nd Hour = 1 Cu.Ft.Min.
Natural Gas Flow Rate At 32.5th Hour = 0.0 Cu.Ft.Min.

TABLE XXI (Continued)

Thermocouple #	Time (Hr.) 28.00	28.25	28.50	29.00	30.00
1	956	947	947	947	947
2	813	819	820	822	829
3	579	584	588	591	600
4	297	298	300	304	308
5	387	389	390	393	398
6	395	333	332	335	336
7	373	360	360	358	358
8	50	52	60	60	63
9	203	207	207	208	210
10	276	277	277	280	281
11	192	192	194	195	197

TABLE XXI (Continued)

Thermocouple #	Time (Hr.) 31.00	32.00	32.25	32.50	33.00
1	939	937	961	986	995
2	831	847	867	871	792
3	601	603	608	603	572
4	315	319	319	320	317
5	405	406	407	408	404
6	314	336	339	338	335
7	360	358	360	361	360
8	66	70	72	74	59
9	212	213	215	212	195
10	284	287	285	283	271
11	200	200	200	201	196

TABLE XXI (Continued)

Thermocouple #	Time (Hr.) 33.0	33.50	34.00	34.50
1	980	832	820	780
2	784	757	732	712
3	564	549	538	516
4	317	316	314	310
5	402	401	398	381
6	336	335	331	331
7	350	356	354	359
8	58	53	48	43
9	192	185	178	168
10	267	264	258	240
11	192	190	189	172

T1 = Temperature Of Front Of Primary Chamber
T2 = Temperature Of Side Of Primary Chamber
T3 = Temperature Of Front OfSecondary Chamber
T4 = Temperature Of Side Of Secondary Chamber

TABLE XXII

WALL TEMPERATURE PROFILES (RUN #5)
(Centigrade)

Time(Hr.)	T1	T2	T3	T4
0.25	30	30	29	-
1.00	30	32	29	-
2.00	30	32	29	-
3.00	30	33	-	-
4.00	30	33	-	-
5.00	32	33	-	32
6.00	34	35	-	32
7.00	34	37	-	33
8.00	36	38	30	33
9.00	36	39	-	-
10.00	38	39	30	34
11.00	38	40	31	34
12.00	38	41	31	35
13.00	39	42	31	36
14.00	40	43	-	36
15.00	40	45	32	-
16.00	40	49	33	-
17.00	41	52	33	-
18.00	42	54	33	-
19.00	42	55	34	38
20.00	43	57	34	39
21.00	44	59	35	-
22.00	44	60	35	-
23.00	44	62	36	-
24.00	46	63	36	41
25.00	50	65	36	42
26.00	52	67	37	44
27.00	52	68	37	45
28.00	54	70	37	45
29.00	54	72	37	46
32.00	58	73	38	47
33.00	58	73	38	47

TABLE XXIII

ORSAT METER READING (RUN #5)
(Percent)

Time(Hr.)	CO_2	O_2
1.0	3.0	13.0
4.0	4.2	12.5
7.0	4.5	10.0
10.0	4.5	9.5
14.0	5.5	8.5
18.0	5.4	8.4
23.0	5.7	8.1
27.0	5.7	7.8
29.0	6.5	7.7
31.0	6.5	6.5
32.5	7.5	8.5
33.0	4.5	14.0

RUN #6 USING NATURAL GAS AND COAL

Pressure = 742 mm Hg
Room Temperature = 64°F
Natural Gas Flow Rate = 1.5 Cu.Ft.Min.
Primary Air Flow Rate = 2.0 Cu.Ft.Min.
Secondary Air Flow Rate = 2.0 Cu.Ft.Min.
Tertiary Air Flow Rate = 2.0 Cu.Ft.Min.
Cooling Air Flow Rate = 9.0 Cu.Ft.Min.
Cooling Water Flow Rate = 0.5 Gal.Per.Min.
Orfice Meter Pressure Drop = 0.5 Inch. of Water
Air Inlet Temperature = 20°C
Water Inlet Temperature = 19°C
Initial Flame Color = Blue
Final Flame Color = Reddish Yellow

TABLE XXIV

TEMPERATURE PROFILES (RUN #6)
(Centigrade)

Thermocouple #	Time (Hr.) 0.00	0.10	0.25	0.50	0.75
1	700	747	742	763	763
2	537	530	529	550	557
3	360	364	372	388	392
4	33	35	36	41	43
5	121	118	117	124	125
6	320	372	403	391	392
7	263	322	360	380	383
8	30	29	30	31	30
9	97	99	99	102	102
10	142	142	144	151	150
11	71	72	72	75	77

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 1.00	1.25	1.50	1.75	2.00
1	775	788	794	802	803
2	546	574	586	594	601
3	389	407	413	418	425
4	45	50	54	56	59
5	125	130	137	139	142
6	397	400	401	402	401
7	390	391	391	390	390
8	30	30	31	30	31
9	102	106	112	113	115
10	151	155	159	162	165
11	78	83	85	85	87

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 2.25	2.50	2.75	3.00	3.30
1	798	805	799	802	806
2	606	615	626	637	657
3	430	434	438	442	454
4	62	65	70	72	80
5	144	148	153	156	165
6	402	402	404	406	407
7	392	391	392	392	392
8	30	31	29	29	29
9	118	121	121	123	128
10	167	170	173	175	181
11	89	92	95	96	102

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 4.00	5.00	5.50	6.00	7.00
1	815	823	825	830	837
2	674	696	705	712	726
3	463	477	485	490	500
4	88	106	115	122	133
5	174	190	197	203	216
6	404	402	397	399	403
7	392	390	391	389	392
8	30	30	32	32	33
9	132	139	140	146	150
10	187	186	201	203	211
11	108	118	121	125	129

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 8.00	9.00	10.00	11.00	12.00
1	847	862	877	887	897
2	740	745	749	761	772
3	511	518	520	528	535
4	150	161	170	185	198
5	232	245	253	266	279
6	414	414	415	418	416
7	393	393	398	398	394
8	33	35	35	37	38
9	156	158	158	164	169
10	217	222	223	228	231
11	136	139	142	147	152

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 13.00	14.00	15.00	16.00	17.00
1	902	907	912	918	907
2	775	783	789	794	783
3	538	548	554	559	549
4	208	217	227	235	242
5	290	298	308	316	322
6	415	417	421	419	433
7	393	391	-	392	400
8	39	40	41	43	49
9	171	173	177	183	188
10	237	239	245	249	252
11	157	159	163	167	172

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 18.00	19.00	20.00	21.00	22.00
1	906	905	908	914	923
2	786	788	790	792	788
3	549	549	550	556	553
4	249	255	260	265	271
5	328	334	339	345	351
6	438	444	445	443	444
7	-	-	408	409	423
8	49	53	55	57	60
9	192	196	198	199	202
10	253	256	258	259	264
11	174	179	181	184	186

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 23.00	24.00	25.00	26.00	27.00
1	921	925	926	931	936
2	793	796	800	805	808
3	558	562	569	571	574
4	277	282	286	292	297
5	355	361	366	370	380
6	447	447	442	441	434
7	424	422	415	420	421
8	62	60	60	57	58
9	209	216	207	212	199
10	262	265	270	272	275
11	189	192	193	195	197

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 27.45	28.00	28.50	29.00	29.50
1	930	925	921	921	919
2	810	806	802	801	800
3	578	577	579	581	585
4	301	305	312	316	323
5	512	511	643	662	667
6	431	432	431	432	434
7	422	423	-	423	425
8	58	60	57	58	57
9	197	199	196	196	198
10	277	277	278	281	283
11	200	202	206	209	216

Coal Is Turned On At 30.50th Hour = 3.00 Lbs.Per.Hr.
Natural Gas Is Turned Off

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 30.00	30.50	30.58	30.67	30.75
1	922	927	962	891	873
2	800	800	830	804	792
3	586	589	586	582	576
4	326	334	336	331	330
5	670	676	555	526	511
6	435	435	435	435	434
7	424	425	430	435	434
8	57	55	57	53	53
9	198	205	201	196	194
10	284	286	289	284	282
11	217	218	217	215	212

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 30.83	30.92	31.00	31.17	31.33
1	863	856	850	844	836
2	787	781	778	773	765
3	570	568	566	563	559
4	328	327	326	326	325
5	503	494	488	477	469
6	433	435	434	437	440
7	428	429	-	430	431
8	52	50	50	50	49
9	189	188	186	184	182
10	279	278	278	275	272
11	211	208	207	205	204

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 31.50	31.75	32.00	32.25	32.50
1	828	823	817	813	808
2	759	753	745	741	735
3	554	552	548	545	542
4	325	324	321	320	319
5	463	454	447	441	434
6	440	440	440	439	438
7	430	432	431	430	429
8	47	48	48	47	47
9	179	178	175	168	167
10	273	270	267	264	265
11	201	201	198	197	196

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 32.75	33.00	33.25	33.50	34.00
1	804	800	795	792	781
2	731	726	722	717	707
3	540	537	535	533	525
4	318	318	316	315	314
5	430	425	421	418	409
6	437	435	439	440	440
7	430	430	428	430	432
8	45	46	45	44	45
9	166	164	160	162	157
10	260	269	258	258	252
11	194	194	193	191	189

TABLE XXIV (Continued)

Thermocouple #	Time (Hr.) 34.50	35.00	35.50	36.00	36.50
1	775	770	763	757	751
2	701	698	692	687	682
3	521	518	512	507	503
4	312	310	304	300	298
5	404	401	397	393	390
6	437	437	440	441	440
7	430	432	432	432	433
8	44	42	41	40	38
9	153	152	150	148	145
10	249	248	246	244	241
11	187	185	183	182	180

T1 = Temperature Of Front Of Primary Chamber
T2 = Temperature Of Side Of Primary Chamber
T3 = Temperature Of Front OfSecondary Chamber
T4 = Temperature Of Side Of Secondary Chamber

TABLE XXV

WALL TEMPERATURE PROFILES (RUN #6)
(Centigrade)

Time(Hr.)	T1	T2	T3	T4
1	25	24	26	25
2	25	26	26	25
3	26	27	-	25
4	26	29	-	26
5	26	30	-	26
6	27	32	-	26
7	27	34	-	26
8	29	35	-	27
9	30	36	-	27
10	32	36	27	27
11	33	38	-	28
12	34	39	-	28
13	34	40	-	29
14	34	42	27	29
15	35	46	28	30
16	35	48	28	31
17	37	52	28	32
18	37	54	28	33
19	38	56	29	34
20	38	58	29	34
21	40	58	29	35
22	41	60	-	36
23	41	61	29	36
24	42	62	29	38
25	43	67	31	41
26	44	69	32	-
27	46	70	32	42
28	47	70	33	43

TABLE XXV (Continued)

Time(Hr.)	T1	T2	T3	T4
29	48	70	33	43
30	50	71	31	38
31	51	72	29	33
32	51	72	29	33
34	50	72	28	31
35	50	72	28	31

TABLE XXVI

ORSAT METER READING (RUN #6)
(Percent)

Time(Hr.)	CO2	O2
2.00	5.0	7.7
5.00	4.2	6.5
8.00	4.2	6.5
11.00	4.5	5.8
15.00	4.2	6.0
19.00	4.5	6.5
22.00	5.0	6.5
26.00	5.0	6.7
27.75	9.0	1.0
30.00	8.8	0.2
30.75	5.0	10.0
31.50	4.6	10.0
32.50	4.0	12.0
33.50	5.0	10.6
34.50	4.5	10.0
35.50	4.4	10.3
36.50	4.3	10.3

APPENDIX B

SAMPLE CALCULATIONS (RUN #4)

Material Balance

Methane:

Density = 0.0448 lb/ft^3 @ 0°C

Density = 0.0415 lb/ft^3 @ 22°C

Air:

Density = 0.0808 lb/ft^3 @ 0°C

Density = 0.0748 lb/ft^3 @ 22°C

Density = 0.0340 lb/ft^3 @ 375°C

Density = 0.0360 lb/ft^3 @ 339°C

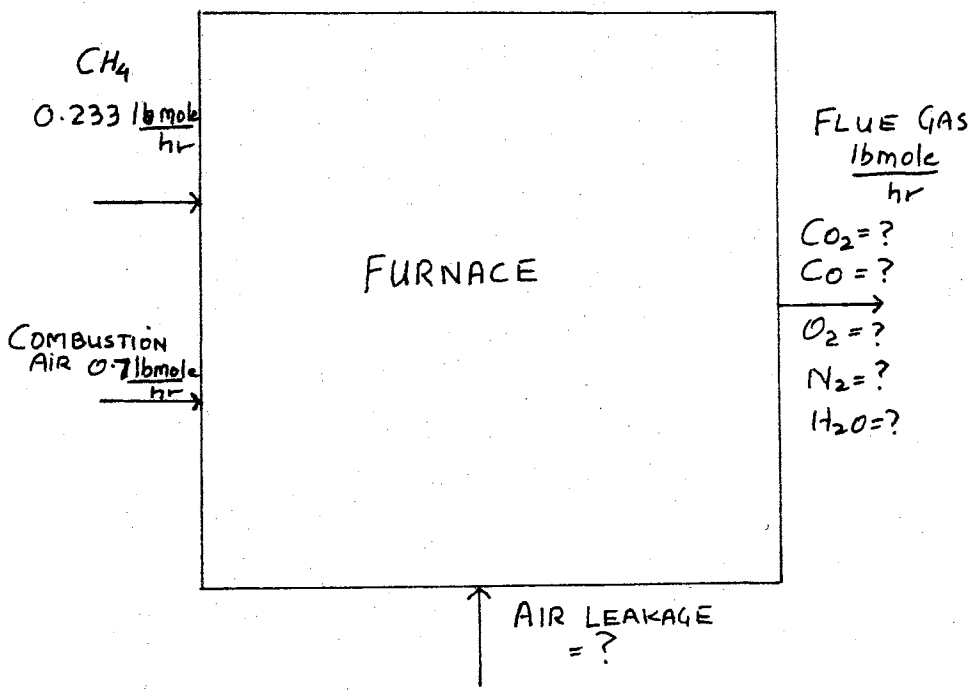
Density = 0.0328 lb/ft^3 @ 400°C

Carbon dioxide:

Density = 0.0501 lb/ft^3 @ 400°C

Water:

Density = 0.0014 lb/ft^3 @ 400°C


CH_4
0.233 lbmole/hr
COMBUSTION AIR 0.7 lbmole/hr
FURNACE
FLUE GAS lbmole/hr
CO_2 = ?
CO = ?
O_2 = ?
N_2 = ?
H_2O = ?
AIR LEAKAGE = ?

Natural Gas(CH_4) = 1.5 c.f.m. = 90 c.f.hr.

# of Moles of CH_4 = 90 ft^3/hr * 0.0415 lb/ft^3 *

1 lb mole/16 lbs

= 0.2330 lb mole/ft^3

Primary Air = 2.15 ft^3/min. = 129 ft^3/hr.

Secondary Air = 2.35 ft^3/min. = 141 ft^3/hr.

Tertiary Air = 2.75 ft^3/min. = 165 ft^3/hr.

# of Moles of Combustion Air = ((129 * 0.0748 + 141 *

0.036 + 165 * 0.0340) ft^3/hr.

* lb/ft^3) / 29 lb/lb moles

= 0.70 lb moles/hr.

Flue Gas Calculations

Wt. Composition of Flue Gas on Dry Basis From Gas Chromatography:

Air = 134.50 = 95.46 %

CO = 0.0 = 0.0 %

CO_2 = 6.4 = 4.54 %

Estimate Water Vapor Present in Flue Gas:

Theoretical Water = 0.466 lb mole H_2O / 0.233 lb mole CH_4

Assume 200 lbs / hr. of Flue Gas is Formed.

For Approximately 100 lbs/hr. of Flue Gas, Wt of H_2O

= 0.466 lb mole * 18 lb/1 lb mole * 1/2

= 4.2 lb/hr

Wt. Composition of Flue Gas on Wet Basis:

Air = 91.61 %

CO_2 = 4.36 %

H_2O = 4.03 %

Mole Composition for 100 lbs of Flue Gas:

Air = 3.16 lb mole/hr. = 90.73 %

CO_2 = 0.099 lb mole/hr. = 2.84 %

H_2O = 0.224 lb mole /hr. = 6.43 %

Flue Gas Outlet Temperature = 400°C

Flue Gas Density = 0.328 * .9073 + 0.0501 * 0.0284 + 0.0014 * 0.0643

= 0.0313 lb/ft^3

Orifice Meter Calculations:

Pressure Drop = (Water Density - Flue Gas Density) * g_c/g * h

= (62.4 - 0.313) lb/ft^3 * 1 lbf/lb * 0.0167 ft.

= 1.04 lbf/ft^3

Velocity of Flue Gas, V:

V = (Co / (1 - ß^4)$^{1/2}$) * (2 * g_c * pressure drop/Flue Gas Density)$^{1/2}$

Orifice meter Constant Co = 0.4

Ratio of Orifice Diameter to Pipe Diameter ß = 0.375

V = 0.404 * (2 * 32.2 * 1.04 / 0.0313) = 18.7 ft/sec.

= 67,328 ft/hr.

Diameter of Stack Pipe = 4 in.

Volumetric Flow Rate of Flue Gas:

$$67{,}328 \text{ ft/hr.} * \pi/4 * (4/12 \text{ ft})^2$$

$$= 5875 \text{ ft}^3/\text{hr.}$$

Mass of Flue Gas = $5875 \text{ ft}^3/\text{hr} * 0.0313 \text{ lb/ft}^3$

$$= 183.9 \text{ lb/hr}$$

Mole Composition for 183.9 lb/hr of Flue Gas:

Air = 5.81 lb mole/hr

CO_2 = 0.182 lb mole/hr

H_2O = 0.412 lb mole/hr

Initial Assumption for H_2O was okay.

Estimation of Air Leakage:

$$CH_4 + 2O_2 \text{ ----------> } CO_2 + 2H_2O$$

0.233 mole	0.466 mole

Air Leakage = $4.76 * 0.466 - 0.7 + 5.81$

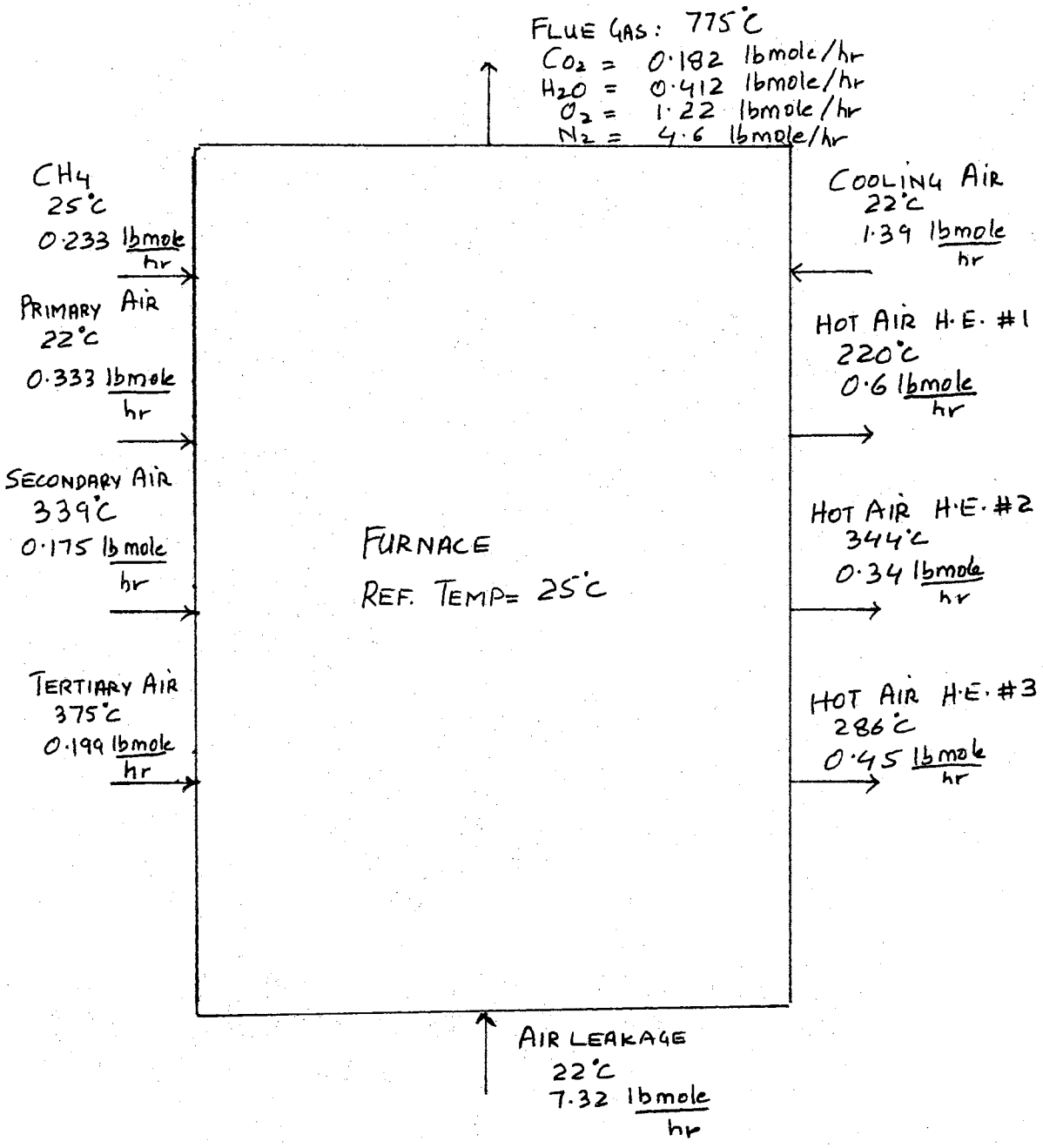
$$= 7.32 \text{ lb mole/hr}$$

$$\% \text{ Error} = \frac{\text{Theoretical } CO_2 - \text{Calculated } CO_2}{\text{Theoretical } CO_2}$$

$$= \frac{0.233 - 0.182}{0.233}$$

$$= 21.88 \%$$

Energy Balance



Calculate Heat Loss due to Conduction:

Thermal Conductivity of Refractory Brick K_r = 0.484 Btu/hr ft°F

Thermal Conductivity of Insulating Brick K_i = 0.169 Btu/hr ft°F

Thermal Conductivity of Steel Cover K_s = 26.2 Btu/hr ft°F

Thickness of Refractory Brick W_r = 0.375 ft

Thickness of Insulating Brick W_i = 0.75 ft

Thickness of Steel Cover W_s = 0.02083 ft

Heat Conduction Surface Area A = 60 ft^2

Wall Temperature inside the Furnace T_i = 750°C = 1322°F

Wall Temperature outside the Furnace T_w = 55°C = 131°F

Heat Loss due to Conduction $Q_c = A * (T_i - T_w)/(W_r/K_r + W^i/K_i + W_s/K_s)$

$= 60 * (1322 - 131)/(0.375/0.484 +$

$0.75/0.169 + 0.02083/26.2)$

$= 14754$ Btu/hr

Calculate Enthalpies:

Reference Temperature = 25°C

Molar Enthalpy $H = Cp(T_1 - T_2)$

$H_F (CH_4) = -74.85$ KJ/mole

H (Air) = 29.0 (22 - 25) = - 0.087 KJ/mole @ 22°C

H (Air) = 29.8 (339 - 25) = 9.36 KJ/mole @ 339°C

$H\ (Air) = 29.85\ (375 - 25) = 10.45$ KJ/mole @ 375°C

$H\ (Air) = 29.5\ (220 - 25) = 5.75$ KJ/mole @ 220°C

$H\ (Air) = 29.82\ (334 - 25) = 9.21$ KJ/mole @ 334°C

$H\ (Air) = 29.6\ (286 - 25) = 7.725$ KJ/mole @ 286°C

$H\ (O_2) = 32.6\ (775 - 25) = 24.45$ KJ/mole @ 775°C

$H\ (N_2) = 30.6\ (775 - 25) = 22.95$ KJ/mole @ 775°C

$$H\ (CO_2) = H_F + \int Cp\ dT$$

$$= -393.5 + (37.15 + 48)/2 * 750/1000$$

$$= -361.6 \text{ KJ/mole @ } 775°C$$

$$H\ (H_2O) = H_F + \int Cp\ dT$$

$$= -241.83 + (33.63 + 37.25)/2 * 750/1000$$

$$= -215.2 \text{ KJ/mole @ } 775°C$$

To Convert KJ/mole into Btu/lb mole multiply by 430.3

n = Lb moles per Hour

Gas	n_{in}	H_{in}	n_{out}	H_{out}
CH_4	0.233	- 32207	-	-
Air (22°C)	8.943	- 37.43	-	-
Air (339°C)	0.175	4027.5	-	-
Air (375°C)	0.199	4496	-	-
Air (220°C)	-	-	0.6	2474
Air (344°C)	-	-	0.34	3963
Air (286°C)	-	-	0.65	3324
O_2 (775°C)	-	-	1.22	10520
N_2 (775°C)	-	-	4.60	9875
CO_2 (775°C)	-	-	0.182	- 156895

H_2O (775°C) - - 0.414 - 92619

Total Heat Loss $Q = \Sigma(n * H)_{out} - \Sigma(n * H)_{in} - Q_c$

$= - 3326 - 14754$

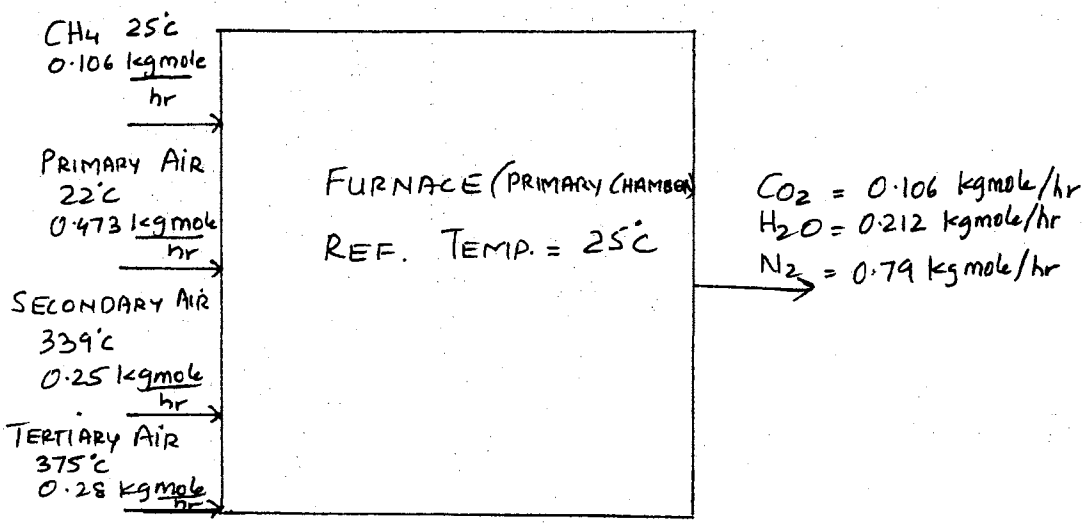
$= - 18080$ Btu per Hr.

Theoretical Adiabatic Flame Temperature

n = Kg mole per hour

Basic Equation:

$$\Sigma (n * H)_{out} = \Sigma (n * H)_{in} - n_{fuel} * H_{comb}$$



Evaluate right-hand side Equation:

$$(n * H)_{in} = \Sigma n * \text{Avg Cp} (T_2 - T_1)$$

$$n_{in} * H_{in} \text{ (Air) @ } 22^{\circ}C = 0.473 * 29 (22 - 25)$$

$$= - 0.041 \text{ KJ/hr}$$

$$n_{in} * H_{in} \text{ (Air) @ } 339^{\circ}C = 0.25 * 29.45 (339 - 25)$$

$$= 2.31 \text{ KJ/hr}$$

$$n_{in} * H_{in} \text{ (Air) @ } 375^{\circ}C = 0.28 * 29.5 (375 - 25)$$

$$= 2.89 \text{ KJ/hr}$$

$$(n * H)_{in} = 5.17 \text{ KJ/hr}$$

$$n_{fuel} * H_{comb} = 0.106 * (-890.36)$$

$$= - 94.39 \text{KJ/hr}$$

Sum of right-hand side of Equation :

$$= 99.56 \text{ KJ/hr}$$

Evaluate Left-hand side of Equation :

$$\sum (n * H)_{out} = (n * H_{vap})_{H2O} + \int \sum n * Cp \, dT$$

$$n * Cp\ (CO_2) = 3.83 + 4.49 * 10^{-3} T - 3.06 * 10^{-6} T^2 + 7.91 * 10^{-10} T^3$$

$$n * Cp\ (H_2O) = 7.09 + 1.46 * 10^{-3} T + 1.612 * 10^{-6} T^2 - 7.617 * 10^{-10} T^3$$

$$n * Cp\ (O_2) = 22.91 + 1.74 * 10^{-3} T - 4.52 * 10^{-6} T^2 - 2.27 * 10^{-10} T^3$$

$$\sum n * Cp = 33.83 + 7.69 * 10^{-3} T - 3.07 * 10^{-6} T^2 - 2.24 * 10^{-9} T^3$$

Divide by 1000 to convert J into KJ

$$(n * H_{vap})_{H2O} = 0.212 * 44$$

$$= 9.33 \text{ KJ/hr}$$

Left- Hand side of Equation :

$$= 33.83 * 10^{-3} T + 3.85 * 10^{-6} T^2 + 1.024 * 10^{-9} T^3 - 5.6 * 10^{-13} T^4 + 8.48$$

Rearrange the whole Equation :

$$5.6 * 10^{-13} T^4 - 1.024 * 10^{-9} T^3 - 3.85 * 10^{-6} T^2 - 33.83 * 10^{-3} T + 91.2 = 0$$

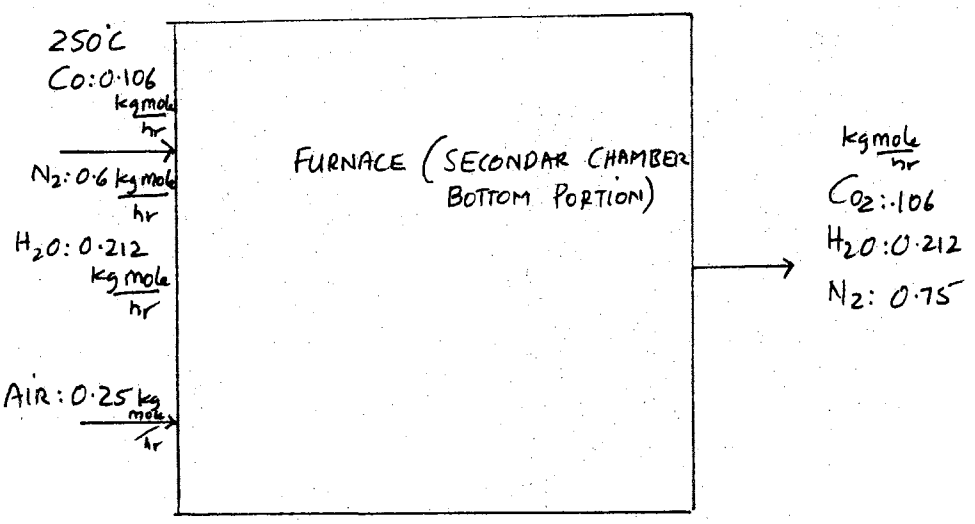
Adiabatic Flame Temperature = 2200°C

Theoretical Flue Gas Exit Temperature

n = Kg mole per hour

Basic Equation based on adiabatic conditions :

$$\Sigma(n * H)_{out} = \Sigma(n * H)_{in} - n_{fuel} * H_{comb}$$



Evaluate right-hand side of Equation:

$$(n * H)_{in} = (n * H_{vap})_{H2O} + \Sigma n * \text{Avg Cp} (T_2 - T_1)$$

$$n_{in} * H_{in} (CO) @ 325°C = 0.106 * 29.8 (325 - 25)$$

$$= 0.95 \text{ KJ/hr}$$

$$n_{in} * H_{in} (N_2) @ 325°C = 0.60 * 29.6 (325 - 25)$$

$$= 5.33 \text{ KJ/hr}$$

$$n_{in} * H_{in} (\text{Air}) @ 325°C = 0.25 * 29.8 (325 - 25)$$

$$= 2.24 \text{ KJ/hr}$$

$$n_{in} * H_{in} (H_2O) @ 325°C = 0.212 * 35 (325 - 25)$$

$$= 2.23 \text{ KJ/hr}$$

$$(n * H_{vap})_{H2O} = 0.212 * 44 = 9.33 \text{ KJ/hr}$$

$n_{fuel} * H_{comb} = 0.106 * (-283)$

$= - 30$ KJ/hr

Sum of Right-hand equation :

$= 50.1$ KJ/hr

Evaluate Left-hand side of Equation :

$\sum (n * H)_{out} = (n * H_{vap})_{H2O} + \int \sum n * Cp \, dT$

$n * Cp\ (CO_2) = 3.83 + 4.49 * 10^{-3} T - 3.06 * 10^{-6} T^2 + 7.91 * 10^{-10} T^3$

$n * Cp\ (H_2O) = 7.09 + 1.46 * 10^{-3} T + 1.612 * 10^{-6} T^2 - 7.617 * 10^{-10} T^3$

$n * Cp\ (N_2) = 21.75 + 1.64 * 10^{-3} T + 4.29 * 10^{-6} T^2 - 2.15 * 10^{-10} T^3$

$\sum n * Cp = 32.67 + 7.59 * 10^{-3} T - 2.84 * 10^{-6} T^2 - 2.21 * 10^{-9} T^3$

Divide by 1000 to convert J into KJ

$(n * H_{vap})_{H2O} = 0.212 * 44$

$= 9.33$ KJ/hr

Left- Hand side of Equation :

$= 32.67 * 10^{-3} T + 3.80 * 10^{-6} T^2 + 0.947 * 10^{-10} T^3 - 5.53 * 10^{-13} T^4 + 8.51$

Rearrange the whole Equation :

$5.53 * 10^{-13} T^4 - 0.947 * 10^{-10} T^3 - 3.80 * 10^{-6} T^2 - 32.67 * 10^{-3} T + 41.5 = 0$

Exit Flue Gas Temperature = 1150°C

VITA[2]

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